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ACOUSTIC FISH RECONNAISSANCE

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In memoriam
Irina B. Andreeva, Ph.D.,
a leading world expert in acoustics

Preface

Commercial reconnaissance of fish and other aquatic items is achieved by various methods and means. One of the main technical means of search and reconnaissance is acoustic location.

Acoustic fish location has recently been widely applied to fisheries. It enables efficient investigation of wide expanses of water, location of fish concentrations, determination of their density and depth, estimation of the commercial significance, and a targeted catch. Acoustic technique has proved to be indispensable to fish reconnaissance and fisheries. Mass application of acoustic equipment on search and commercial vessels has made it possible to increase the efficiency of fishing and targeted trawling of concentrations by commercial fleets, thereby enhancing the industrial exploitation of the World Ocean resources.

The modern development of fish location is characterized by the aspiration to a wider practical application of the acoustic method of biomass estimation. This has been motivated by stock reduction of some basic species and by the introduction of 200-mile fishery zones on continental shelves. In the near future, wide-scale inculcation of the acoustic method of biomass estimation should lead to an updated system of observation and control in fisheries, which, in turn, will promote greater efficiency in the exploitation of marine resources.

For scientific search and fishing purposes, there are many acoustic instruments that allow fish detecting at practically any depth. There are instruments for estimating the density of concentrations, their size composition, and their movement direction and speed. The application of locating equipment under various conditions contributes a great deal to both theoretical and practical investigations. All this enabled developing and deepening the theory of fish location, improving the fish-finding technique as well as the methods of its use.

A myriad of publications deal separately with the theoretical, technical, and practical aspects of fish location. The various applications of acoustic instruments in fisheries are presented; questions of species, size, and quantitative interpretation of readings are considered. The results of these studies are given, in particular, in the proceedings of the International Symposia and Conferences on Fisheries Acoustics and in a great number of separate papers. Specific aspects of the overall problem of acoustic fish reconnaissance are considered in the books. However, until now, there has not been any work that presents the subject systematically, detailing all major aspects of applying acoustic equipment in commercial fish reconnaissance and offering sufficient analysis of the possibilities of fish-finding technique.

The proposed monograph is the first overview of the theoretical and practical theses, encompassing all the main aspects of acoustic search, detection, interpretation, and estimation of populations of fish and other aquatic items for the purposes of tracking commercial concentrations and making decisions for their exploitation. The authors integrate the numerous problems into the general term *Acoustic Fish Reconnaissance*. The book considers technical and biological arguments, both of which impact upon the efficiency of operation of fish-finding instruments. The essence of the physical phenomena occurring in the process of acoustic fish location is closely connected to the practical knowledge gained while applying instruments during acoustic surveys and fisheries. Special attention is paid to questions of theory and practice of accounting surveys for quantitative estimation of biological resources and fishing conditions in traditional fishing areas.

The analysis of various aspects of the application of acoustic technique in fish reconnaissance is based mainly on the results of the authors' investigations. The results of estimating the applicability of fish-finding instruments, obtained by Dr. Yudanov during the research period, together with recommendations on the development and improved application of the acoustic techniques for fishing fleets, make up a considerable part of the book. Dr. Yudanov outlined the results of his work in a monograph (Yudanov, K.I., *Interpratation of Echograms of Hydroacoustics Fish-Finding Instruments*, Vilim, E., Trans., Keter Press, Jerusalem, Israel, 101, 1971). The main theses of the book, related to the method of aquatic biomass estimation, were developed by the authors during their joint research at the All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), Moscow, aimed at the inculcation and applied use of acoustic surveys. The main results of these studies are published in the peer-reviewed proceedings of the International Symposia and Conferences on Fisheries Acoustics.

The book is completed by the research conducted over the last 15 years. Dr. Kalikhman, working at the Kinneret Limnological Laboratory of Israel Oceanographic and Limnological Research Ltd., has further developed and considerably deepened the theoretical aspects of acoustic surveys. The results of his research are published in a reference book on environmental monitoring (Kalikhman, I., *Patchy Distribution Fields: Acoustic Survey Design and Reconstruction Adequacy,* in *Environmental Monitoring*, Wiersma, G.B., Ed., CRC Press, Boca Raton, 465, 2004) and international scientific journals including *Environmental Monitoring and Assessment*, *ICES Journal of Marine Science*, *Freshwater Biology*, and others. The authors' achievements have thus been accepted by the International Acoustical Society and have augmented the world's knowledge in the area of acoustic fish reconnaissance. The book also presents in a systematic form the main results of the other experts dealing with application of acoustic instruments for investigations and fisheries needs.

Dr. I.L. Kalikhman
Dr. K. Yudanov

Acknowledgments

Dr. Irina B. Andreeva, who worked as a leading scientist at the Institute of Acoustics, Moscow, was an internationally acclaimed expert in the field of acoustics of the ocean. She was one of the first to understand the nature of sound-scattering layers, and she developed the theory of resonance acoustic scattering on air bubbles. Dr. Andreeva, who was a State Prize laureate, published more than 100 papers (the majority of which have been translated into English) and three books. Despite her busy schedule, Dr. Andreeva found time to read the manuscript of the present book and offered constructive criticism and suggestions. I honor her memory.

Unfortunately, it was not destined that Dr. Kir I. Yudanov would be present upon publication of the book; he passed away on December 25, 2004. Up to the last moment, he remained faithfully at work on the book. His dedication, persistence, and adherence to principles set an example for everyone. The creation of our collaborative work following 15 years of separation confirms the sincerity of our friendship and the efficiency of our joint endeavor. I also honor his memory.

On behalf of Dr. Yudanov and myself, I wish to express my sincere gratitude to all those who, by their favorable response, promoted the publication of this book: to the leading world expert in environmental monitoring, Dr. G. Bruce Wiersma, Professor of Forest Resources, University of Maine, Orono, Maine; to reviewer Dr. Charles H. Greene, Director, Ocean Resources and Ecosystems Program, Cornell University, Ithaca, New York; and to another anonymous reviewer.

I am indebted to Dr. Isaac Gertman, Boris Katznelson, and Irina Lunin for their invaluable help and expertise in modern computer software; to Hana Bernard for her skillful graphics; and to William Bishop and Miryam Fridman for the final editing of the text. I am thankful to my wife, Tatiana, and to my daughter, Dinah, for providing care and creating favorable working conditions during the book preparation. I am grateful to the United States Agency for International Development, the United States–Israel Binational Science Foundation, the Rich Foundation, the Israel Ministry of Science and Technology, and the Israel Ministry of Absorption, whose financial support made the creation of the present book possible.

I accept all responsibility for any mistakes that might be found in the book.

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He graduated in 1971 from the Moscow Energetic Institute, with an M.S. degree in radio-physics, and obtained his Ph.D. degree in fisheries acoustics from the All-Union Research Institute of Fisheries and Oceanography (VNIRO).

From 1973 to 1990, Dr. Kalikhman was a senior scientist at VNIRO. In 1990, he repatriated to Israel, and since 1990 he has been working as a senior scientist at Israel Oceanographic and Limnological Research Ltd.

Dr. Kalikhman participated in the research aimed at generalizing the theory and creating a single acoustic method of marine biomass estimation. He played a major role in elaborating a manual of acoustic surveys and methodological recommendations on carrying out multidisciplinary surveys of fishing conditions. Dr. Kalikhman's scientific interests include problems of acoustic survey design, spatial patchiness, and ecosystem component interaction. He developed a mathematical model for determining parameters of acoustic surveys on the basis of statistical characteristics of patchy distributions and a method of identification of correlation zones for aquatic ecosystem component distributions.

Dr. Kalikhman has written more than 60 scientific papers and two books. He participated in the International Symposia on Fisheries Acoustics (Aberdeen, Scotland, 1995, and Montpellier, France, 2002).

A biographical profile of Dr. Kalikhman appears in *Marquis Who's Who in Science and Engineering*.

DR. K.I. YUDANOV (1927–2004)

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Dr. Yudanov led or participated in theoretical and experimental works aimed at improving acoustic instruments, interpreting their readings, and developing research methods. He paid special attention to elaborating and improving an acoustic method of assessing commercial resources and fishing conditions. He prepared several comprehensive works in this discipline, which were inculcated in the practice of acoustic surveys.

Dr. Yudanov wrote more than 100 scientific papers and two monographs. He participated in the International Symposia on Fisheries Acoustics, including the organization and conduction of the Soviet-American Symposium in Cambridge, Massachusetts, in 1979, which drew many international experts.

Introduction

The present monograph is engaged with the questions of sound scattering by marine animal concentrations, search and detection of items, species and size interpretation of echo signals, and quantitative estimation of biological resources and fishing conditions. The problems, under the term “Acoustic Fish Reconnaissance,” can be divided into nine major groups; each group of questions forms a corresponding chapter.

Chapter 1 reflects the problem of sound scattering by commercial items. Knowledge of the regularities of scattering is crucial for establishing the dependence of value and pattern of echo signals on the parameters of aquatic animal concentrations. Results of experimental measurements of acoustic characteristics of individual items are given regarding swim bladder and bladderless fish as well as other marine animals, while the analytical solution of the problem is obtained pertaining to swim bladder fish alone. Regularities of the Rayleigh, coherent, and multiple sound scattering by item concentrations are considered in this chapter in detail. Classification of echo signals allows one to detect and correctly interpret aquatic animals in practically all important cases. The statistical analysis and treatment of fluctuations of echo signals makes it possible to substantially increase the range of detection of commercial items by acoustic equipment.

Chapter 2 describes the question of determining the scouting characteristics of acoustic instruments. The reasons for the specific requirements in the mentioned characteristics are the differences in the reflectivity of concentrations of marine animals, the necessity to detect them, and species and quantitative interpretation of echo signals. The first, and most important, condition is the maximal range and the zone of detecting aquatic animals by an acoustic instrument; another is sufficiently high resolution by range and angle. This chapter shows how characteristics of fish-finding devices can be determined and to which extent they satisfy the required demands. The rational choice of acoustic instruments’ major parameters is considered as well.

Chapter 3 discusses questions related to the search for aquatic animals with acoustic instruments. Search is a step in a process of reconnaissance aimed at the detection of commercial fish concentrations. Search possibilities largely depend upon the shapes of distributions of marine animals by the water area and depth, which are considered in detail. The methods of optimizing the grid in the geological reconnaissance of minerals, based on the solution of the Buffon-Barbier problem, are applied to the acoustic search for commercial items. The tactics of a background survey are usually based upon the condition of commercial significance of a population. Examples of choosing the distance between transects of such a survey are given regarding various dimensions and shapes of concentrations.

Chapter 4 addresses the problem of efficiency of detecting commercial fish concentrations with acoustic instruments. This chapter examines the general limiting factors in detecting marine animals by echo sounder, consisting of a spherical wave front and masking of bottom fish by the unevenness of the ground. The peculiarities of detecting commercial items are considered in detail, such as a nonuniform scale of registrations, wide transducer directivity diagram, or additional reflections inside the concentration, from the sea surface and the bottom. Possibilities of detecting fish concentrations by sonar with various bottom compositions and heights of unevenness of the ground are also examined. Questions connected to the angle of incidence of the acoustic beam are discussed. Methods of experimental measurements of parameters of equipment over special proving grounds are described.

Chapter 5 deals with the questions of species and size interpretation of recordings of commercial item concentrations. Determining the composition of concentrations by acoustic data is very important in fisheries, in search and investigation, when studying the distribution and behavior of fish and other marine items; in estimating their commercial significance; and in controlling the state of stocks, etc. Interpretation of recordings is done visually, by analyzing echograms or automatically, from readings of specially elaborated equipment. For the latter purpose, devices are developed operating at some specific optimal frequency or at the resonance frequency of the swim bladder, using the dependence of the target strength on the fish length (the method of Craig and Forbes) and instruments with dual, conic, and split beams.

Chapter 6 encompasses questions related to quantitative interpretation of recordings of commercial item concentrations. The quantitative estimation is important in fisheries for detecting and targeted fishing of the densest areas of concentrations, when studying the biological regularities of behavior and distribution of sea animals and while assessing fishing resources. The analytical expressions for determining the density of commercial concentrations given are, in fact, the algorithm of computer treatment of acoustic survey data. The step-by-step and through methods of calibration of acoustic instruments are considered, as well as the method of intercalibration of devices. Possibilities of quantitative interpretation of recordings of echo sounder and sonar are examined regarding various types of behavior and distribution of commercial items.

Chapter 7 considers various aspects of the problem of acoustic surveys of biological resources and fishing conditions. The chapter discusses questions related to the tactics of surveys (including choice of survey periodicity, initiation, type, mode and duration), collection and treatment of data (determination of ichthyologic and oceanographic characteristics), and acoustic survey errors (the bias of biomass estimate and unbiased error of fish distribution). Practice and perspectives of acoustic surveys are discussed and so are the main results of the surveys, currently carried out in the majority of fishing regions of the World Ocean. A method of determining the economical efficiency of acoustic surveys is suggested; the peculiarities of the method regarding surveys of fishing conditions and those of biological resources are considered.

Chapter 8 introduces the reader to fisheries-acoustic surveys, which can only be carried out in the areas where a fishing fleet operates. For precise and operative estimation of fishing conditions and the state of stocks, it is suggested to use not only acoustic data but also fisheries information. The methods of determining the commercial significance of concentrations from acoustic and commercial data are considered in this chapter in detail. In most cases, the accuracy of a fisheries-acoustic survey is the same as that of an acoustic survey. Due to the short duration of a fisheries-acoustic survey, its data can be used to follow processes in dynamics and reveal ecosystem relationships. Knowledge of regularities of behavior and distribution of items will enable a more precise forecasting of fishing conditions and the state of stocks.

Finally, Chapter 9 conveys the importance of passing observations and surveys conducted on fishing vessels. If necessary, a fishing vessel can be temporarily equipped with acoustic instruments, the so-called electronic attachment to an echo sounder. This chapter presents, in detail, a simplified variant of calibrating an acoustic instrument as well as estimating the commercial significance and density of fish concentrations by catches. The wide inculcation of passing observations and surveys in the fishing fleet will allow monitoring of biological resources on a global scale without carrying out expensive acoustic surveys.

List of Symbols

B	tons/mile^2	Structure function
c	m/s	Sound speed in water
C	tons/mile^2	Scale value for integrator
C_1	\$/day	Cost per day
C_A	V^{2}m^2	Acoustic constant of fish-finding instrument
C_{cs}	tons/hour	Scale value for commercial significance
C_{EA}		Electro-acoustic constant of equipment
C_I	1/V^{2}s	Integrator constant
d	cm or m	Diameter
EE	\$	Economic expenses
EF	\$	Economic effect
ER	\$	Economic return
f	kHz	Frequency
f_{imp}	1/s	Ping rate
F		Distribution or correlation function
G		Directivity function or factor
h or H	m	Thickness
I	W/m^2	Sound intensity
k or K		Coefficient of proportionality
K_δ		Coefficient of reliability of reception
l	m or mile	Length
m_s		Coefficient of area scattering
m_v	1/m	Coefficient of volume scattering
M		Readings of integrator
M_1		Average readings of integrator per ping
n or m		Number (of items, species, impulses, etc.)
p		Probability
p	N/m^2 or Pa	Static or acoustic pressure
P	W	Acoustic power
P_1	\$/ton	Profit per ton
Q	tons/hour	Catch per time unit or commercial significance
r, a, b, L, or D	cm, m, or mile	Distance or dimension
R	cm, m, or mile	Radius
R_{eq}	cm	Radius if equivalent sphere
S	cm^2, m^2, or mile^2	Area or surface
t	ms or s	Time
T	ms, s, or day	Time interval
TS	dB	Target strength
T_w	tons/day	Rate of biomass change
U	V	Voltage
v	mm/s, m/s, or knot	Speed
V	m^3	Volume
w	g or kg	Mass of individual item

W	tons	Biomass or stock
W_{trawl}	m^3/hour	Technical productivity of fishery complex
x, y	m or mile	Current coordinate
X, Y	mile	Length or width of area
X_1–X_4		Dimensionless parameters of scattering medium
Y	tons	Catch
α	dB/km or dB/m	Coefficient of spatial attenuation of sound in water
β	° or rad	Inclination angle
β_1	dB	Reflection loss
γ		Coefficient of axis concentration
δ	Rayleigh	Optical or acoustical thickness
δ_L	m	Tangential resolution
δ_r	cm or m	Resolution by distance
δ_s		Coefficient of recognition
δ_θ	° or rad	Resolution by angle
Δ	m or mile	Increase (of thickness, length, etc.)
Δf	Hz or kHz	Frequency band
ε		Relative error
θ	° or rad	Insonification, detection, or orientation angle
θ_{eff}	° or rad	Effective angle of detection
λ	cm	Wavelength
μ		Gain
ν		Coefficient of variation
Π	m^2	Energetic potential
ρ	kg/m^3	Water density
ρ_s	tons/mile^2	Area density
ρ_v	1/m^3	Volume density
σ	cm^2	Acoustic section of item
τ	ms	Impulse duration
φ	° or rad	Azimuth angle
Φ	m or mile	Perimeter
χ	µV/Pa	Sensitivity of transducer in reception
Ψ	steradian	Integral directivity function or factor

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Afterword

In conclusion, we would like to emphasize that the operations of commercial and research vessels are inconceivable at present without the use of acoustic instruments for various purposes. Acoustic equipment is used for searching and detecting as well as for species, size, and quantitative estimation of commercial concentrations and their targeted fishing. Acoustic equipment for the quantitative estimation of marine biomass is very important. In connection to this, in our opinion, different methods of conducting acoustic surveys and passing observations must be more greatly developed.

Disposing the acoustic account of commercial items, it became possible to receive quantitative dependences of the impact of environmental factors and fisheries on the ecosystems of water bodies. The establishment of the regularities of quantitative development of life will allow a more adequate forecasting of fish stocks and catch, taking into account their reproduction. Hopefully, the knowledge of quantitative ecological regularities will be required not only in solving problems of preserving commercial resources from extermination, but also in conducting a rational fishing industry and increasing the productivity of the oceans.

1 Sound Scattering by Commercial Items

Studies of the regularities of sound scattering by concentrations of fish and other aquatic items, establishing the dependencies of the character and intensity of echo signals on the size and density of their concentrations, allow one to perform many practical tasks related to detection of commercial concentrations, interpretation of readings of acoustic fish-finding instruments and, most importantly, the quantitative estimation of marine biomass by acoustic methods. Knowledge of the regularities of scattering also makes it possible to develop the technique of presentation of reflected echo signals in a form convenient for use in acoustic reconnaissance. Therefore, the study of the reflectivity of marine items and the possibility of detecting echo signals from them is of primary importance.

1.1 CHARACTERISTICS OF THE REFLECTIVITY OF AQUATIC ANIMALS

In fisheries acoustics, reflective properties of items are usually characterized by sound scattering in the back direction. Two factors are known to affect sound scattering by an item: (1) the dimensions of the item in the direction of acoustic wave propagation; and (2) the sectional area of the scatterer perpendicular to acoustic wave propagation. In other words, the longitudinal dimension of the entire item and its individual elements determine the qualitative aspect of the scattering, while the quantitative aspect is determined by the cross-sectional area.[1]

Qualitative characteristics of the reflectivity of an individual item and concentrations are usually expressed in dimensionless parameters. The pattern of scattering of an individual item depends, first of all, on the dimensionless parameter, which is determined by the ratio of the entire length of item L_{fish} to the length of wave λ; i.e.,

$$X_{fish} = L_{fish}/\lambda \qquad (1.1)$$

When analyzing the peculiarities of sound scattering (interference phenomena, multiple scattering), an account of the structure of individual items and their concentrations is also required. Thus, the structure of an individual scattering item is characterized by the parameters

$$X_1 = L_1/\lambda \qquad (1.2)$$

$$X_2 = L_2/\lambda \qquad (1.3)$$

where L_1 is the distance between individual elements inside the item, L_2 is the dimension of the item in the direction of acoustic wave propagation, and λ is the acoustic wavelength.

Regarding the vertical location, the most important internal dimensions of the fish are the thickness of its swim bladder and the distance between the outer flesh layer and the spine. These distances usually approximate five hundredths of the total length of the fish; i.e., $L_1 = 0.05L_{\text{fish}}$. The value L_2 is determined by the thickness of the entire fish, which usually approximates two tenths of its length; i.e., $L_2 = 0.2L_{\text{fish}}$.

The structure of an item concentration is characterized by:

$$X_3 = L_3/\lambda \tag{1.4}$$

$$X_4 = L_4/\lambda \tag{1.5}$$

where L_3 is the average distance between individual items and L_4 is the dimension of a scattering volume in the direction of acoustic wave propagation.

The average distance between individual items in the concentration can be calculated as $L_3 = 0.55/\rho_v^{1/3}$ if the volume density of a fish concentration ρ_v is known.[2] The value L_4 is equal to half the length of a transmitted impulse in the water; i.e., $L_4 = c\tau/2$.

Using information on the size of marine items and distances between them, we can calculate the values of the dimensionless parameters X_{fish} and X_1 through X_4 for different distributions of items, assuming an echo sounder operating frequency equaling 30 kHz (λ = 5.0 cm) and an impulse length τ = 1.0 ms. The results of this calculation are presented in Table 1.1.

Table 1.1 shows that ratios of the dimensions of individual elements of items, entire items, and their concentrations to the wavelength can vary over great ranges; this, in turn, leads to substantial changes in the pattern and the intensity of scattering. As will be shown further, the intensity of the acoustic field scattered by individual items and their concentrations depends to a great extent on the form and dimensions

TABLE 1.1
Qualitative dimensionless parameters of the reflectivity of biological objects

Item	Length L_p (cm)	Density ρ_v (sp/m^3)	X_{fish}	X_1	X_2	X_3	X_4
Plankton	0.1 to 5.0	10^6 to 10	0.02 to1.0	—	0.004 to 0.2	0.1 to 5.0	15
Fish	5.0 to 100	10^2 to 10^{-4}	1.0 to 20	0.05 to 1.0	0.2 to 4.0	2.5 to 240	15
Tuna, sharks, dolphins	100 to 1000	$<10^{-3}$	20 to 200	1.0 to 10	4.0 to 40	110	—

of items, ratios of their dimensions to the wavelength, distance between items in the concentrations, and other factors.

Quantitative characteristics of the reflectivity of an individual item and concentrations are determined by one of the following parameters: acoustic scattering cross section, radius of the equivalent sphere, target strength, or reflection losses.

The acoustic section of backscattering in classical acoustics is determined by the ratio of the power P'_{scat}, scattered by an item in the unit of solid angle in the direction of reception, to the intensity I_{fall} of the incident sound wave; i.e.,

$$\sigma_k = \frac{P'_{scat}}{I_{fall}} = \frac{r^2 I_{scat}}{I_{fall}} \tag{1.6}$$

where r is the distance between the point of reception and an item and I_{scat} is the intensity of scattered sound at the point of reception.

However, the formula for calculating the acoustic sections, which is used in fisheries acoustics, differs slightly from (1.6) and is expressed as

$$\sigma = \frac{P_{scat}}{I_{fall}} = \frac{4\pi\, r^2\, I_{scat}}{I_{fall}} = 4\pi\sigma_k \tag{1.7}$$

In this case, the acoustic scattering cross section is a standard area that produces an ideal all-directional reflection similar to that which would be produced by the real item in a given direction. Though this value is slightly less convenient than σ_k, it is widely used in fisheries acoustics (see, for instance, Reference 3). Therefore, later on, we will only use the values of σ.

The notion of the radius of equivalent sphere R_{eq} is also used. It is connected to the acoustic section by the following relationship:

$$R_{eq} = \sqrt{\frac{\sigma}{\pi}} \tag{1.8}$$

where σ is in m^2 and R_{eq} in m.

The reflectivity of an item is also expressed in practice by target strength. This parameter is the logarithmic expression of the reflectivity of an item. Target strength is determined from the following formula:

$$TS = 10\log\frac{\sigma}{4\pi} \tag{1.9}$$

Sometimes, it is more convenient to express the reflectivity through the target strength per one kilogram of weight. The value of TS_{kg} is expressed by the following correlation:

$$TS_{kg} = TS - 10\log w \tag{1.10}$$

where TS is the average value of target strength and w is the average mass of an individual item in parts of a kilogram.

Sometimes a value opposite in sign to target strength is used. This value is called reflection loss and is determined by the following formula:

$$\beta_1 = 10\log \frac{4\pi}{\sigma} \tag{1.11}$$

The conversion of acoustic section into target strength or reflection loss is usually accomplished with the help of graphs (Figure 1.1).

In locating fish, especially in carrying out surveys, quantitative characteristics of backscattering are most interesting, and are frequently expressed as target strength of backscattering, called target strength of items, for short.

The complexity of phenomena resulting from sound scattering by individual marine items and concentrations still hampers efforts to obtain sufficiently precise theoretical expressions for calculating their acoustic characteristics. Therefore, at present, along with theoretical investigations, experimental studies are carried out on the reflectivity of fish and other marine animals in the laboratory and *in situ*.

Let us examine in detail the quantitative and qualitative characteristics of sound scattering by individual marine items and their concentrations in relation to vertical location.

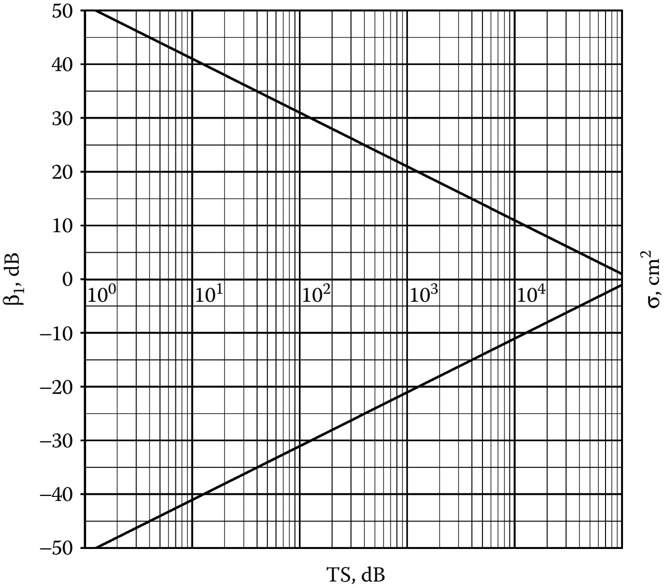

FIGURE 1.1 Graphs for conversion of acoustic sections into target strength and reflection losses.

1.2 SOUND SCATTERING BY AN INDIVIDUAL ITEM

Acoustically, fish and other aquatic organisms are seawater heterogeneities, scattering sound waves in all directions. Scattering of acoustic energy by heterogeneities was thoroughly studied by J.W. Rayleigh[4,5] regarding items whose size is considerably smaller than the wavelength ($X_{fish} << 1.0$). It follows from the Rayleigh law of scattering that the acoustic section of each item is proportional to the acoustic frequency raised to the fourth power and to the item radius raised to the sixth power. Thus, with a twofold increase of the item size, the intensity of scattering increases 64 times.

The regularities obtained by Rayleigh make it possible to plot the distribution of the sound intensity scattered from the angle of insonification; i.e., the so-called spatial indicatrix of scattering. Figure 1.2 shows a plane indicatrix of the Rayleigh scattering; the spatial indicatrix is obtained by rotating plane one around the acoustic axis. The indicatrix of the Rayleigh scattering reveals that scattering forward and backward is identical and is twice as large as that in the perpendicular directions. An important property of the Rayleigh scattering from small items is that only the size of the scattering indicatrix can change, while its form remains constant irrespective of the size and form of small items.

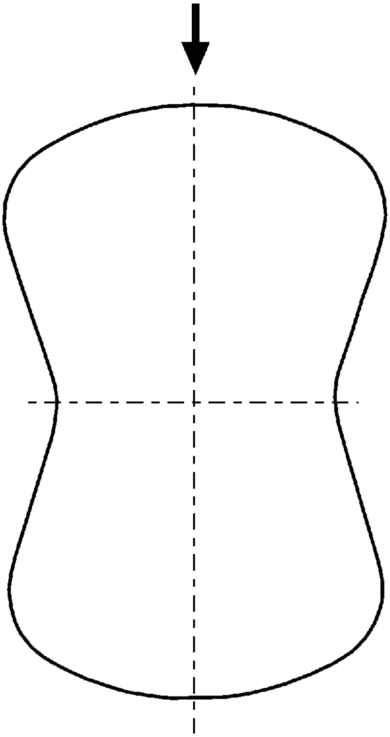

FIGURE 1.2 Indicatrix of the Rayleigh scattering of sound.

These regularities are applicable first to various plankton organisms and young fish, which are considerably shorter than the acoustic wavelength. The value of the acoustic section of such minor items is very small. For some plankton specimens, it can be in the order of 10^{-5} cm^2 or less. Gas bubbles that result from plankton life activity have much greater reflectivity than plankton themselves. Intensive sound scattering is observed, for instance, in areas of rich bloom of phytoplankton when the water is saturated with air bubbles.

Applied to highly resonant items, the Rayleigh law of scattering is true if the size of items does not exceed two tenths of the acoustic wavelength; i.e., $X_2 < 0.2$. However, for marine animals with acoustic properties slightly different from the environment, the Rayleigh regularities of scattering are applicable even though the size of the items is commensurable to the wavelength.

According to the theory of scattering, as the dimensions of the items increase (raising parameter X_2), the scattering intensity also increases, but not as quickly as with the Rayleigh scattering. If the dimensions of fish in the direction of the acoustic energy propagation exceed the wavelength considerably, the theory of scattering becomes more complicated as diffraction phenomena occurring at the surface of fish are involved.

In addition to the surface phenomena, it is necessary to consider the peculiarities of internal reflection of acoustic waves inside a fish. The fish body is a water-like medium; therefore, only a small part of the incident acoustic energy reflects from its surface; the bulk of it penetrates the fish. Once inside the fish, acoustic energy leaves the fish or, after numerous internal reflections, emerges from it in various directions. This leads to deformation of the scattering indicatrix: since the dimensions of the item increase, the indicatrix is continually extending forward.

Sound scattering by the fish is also affected by interference phenomena resulting from superposition of reflections from front and rear parts of the body (swim bladder, head, spine, flesh, etc.) in the direction of the acoustic wave propagation. This leads to strengthening or weakening of backscattering and consequently to the formation of maximum and minimum values of the acoustic section with certain ratios of fish size and the wavelength.

EXPERIMENTAL MEASUREMENTS OF ACOUSTIC CHARACTERISTICS OF FISH

The complexity of phenomena occurring with sound scattering by fish considerably hampers theoretical calculations of acoustic sections of fish; therefore, they need to be found experimentally. In recent years, scientists from many countries have completed extensive experimental investigations of acoustic characteristics of fish in the laboratory and under natural conditions, mostly with application to vertical location (see References 1, 6–17, and other studies).

Figure 1.3 presents some results of experimental measurements of acoustic sections of fish in their vertical insonification from the dorsal side.[1] It shows that the reflectivity of several fish of the same species and size can widely vary. Significant variation in values of fish acoustic sections is caused by individual differences in the exterior, volume of the swim bladder, stomach content, state of sexual products, fattiness, gas bubbles in the stomach and the intestine, and other factors. Figure 1.4

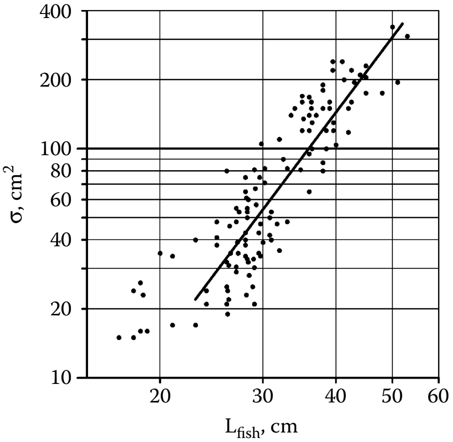

FIGURE 1.3 Experimental dependences of acoustic sections of fish on their length for cod when insonified at dorsal aspect at 30 kHz.

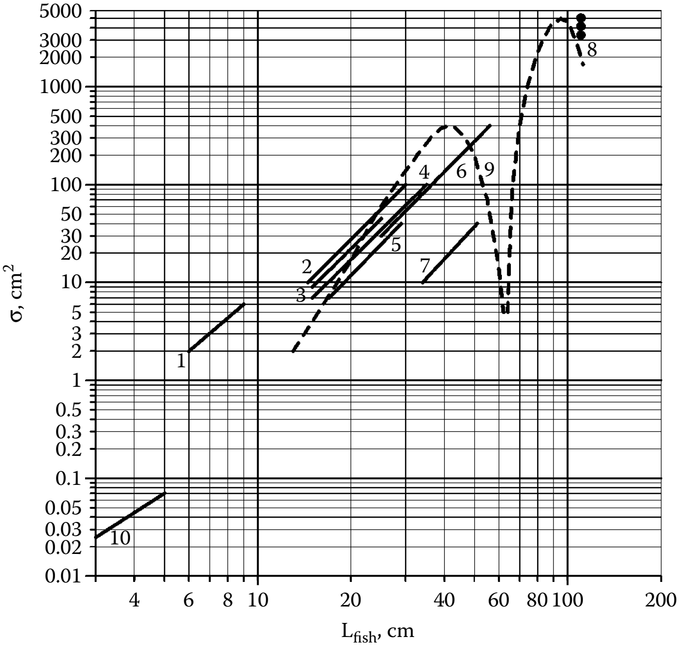

FIGURE 1.4 Experimental dependences of average acoustic sections of various items on their length when insonified at dorsal aspect. Fish at 30 kHz: 1, stickleback; 2, flounder; 3, herring; 4, sea trout; 5, goby; 6, cod; 7, wolffish; 8, seal (for comparison); 9, dependence calculated with L_{fish} = 15–30 cm and λ = 5.0 cm. Plankton at 120 kHz: 10, Antarctic krill.

shows the dependence of the average acoustic sections of various marine items on their length.[1] In rare cases, experimental results for individual specimens of Antarctic krill were obtained in the Antarctic region, when they were separately registered by the echo sounder. As follows from the graphs, the reflectivity of various species differs considerably.

The fish reflectivity greatly depends on its orientation to the insonification direction. Figure 1.5 shows backscattering diagrams plotted at polar coordinates at different angles of insonification (location angle θ) and with the fish rotated in the horizontal plane (with changing azimuthal angle) within 360°.[8] It follows from the figure that the diagram of scattering for larger fish has more abrupt changes from maximum to minimum, a greater number of lobes, and consequently narrower lobar width. Maximum values of acoustic sections occur with the reflection of acoustic waves from the side surface of the fish body; minimum values correspond to the head and the tail. In Figure 1.6, the space diagram of sound backscattering by fish is shown.[18]

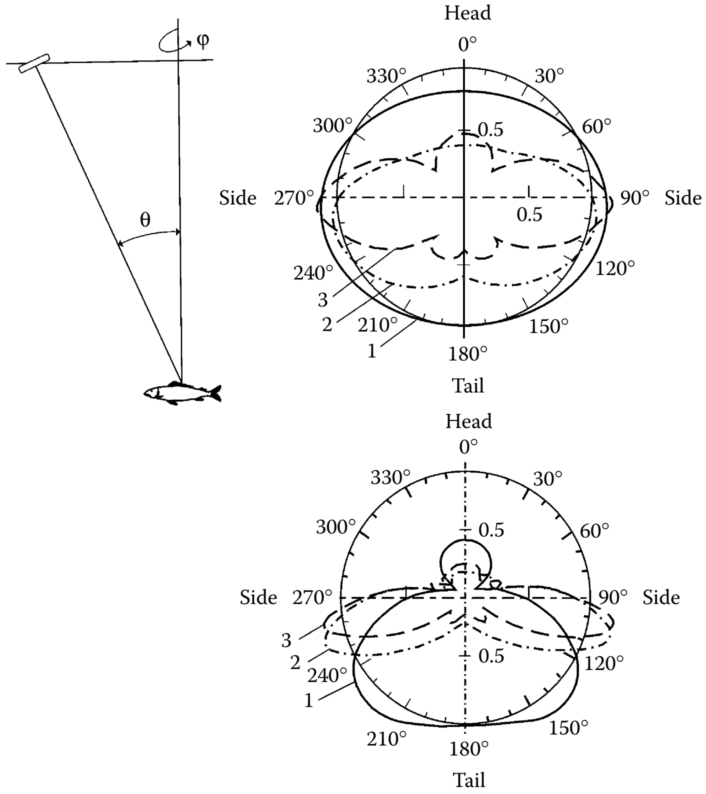

FIGURE 1.5 Left: Scheme of measurements of acoustic sections of fish at various azimuthal and insonification angles. Right: polar diagrams of the sound backscattering by fish at 30 kHz at various insonification angles (1, θ = 5°; 2, θ = 20°; 3, θ = 35°); Top: herring 14 cm long; Bottom: herring 32 cm long.

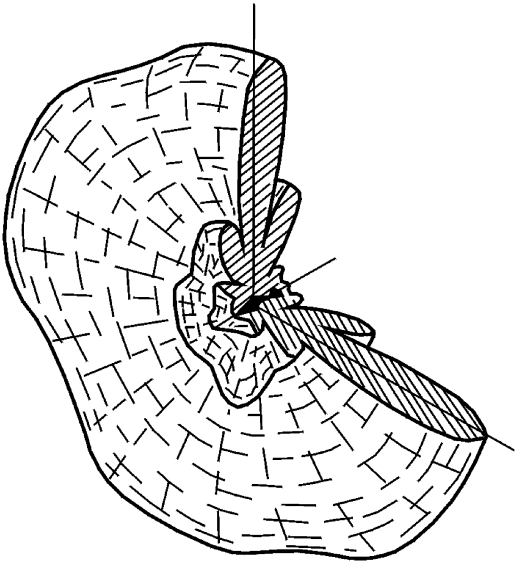

FIGURE 1.6 Spatial diagram of the sound back scattering by fish with $L_{fish}/\lambda = 5.0$.

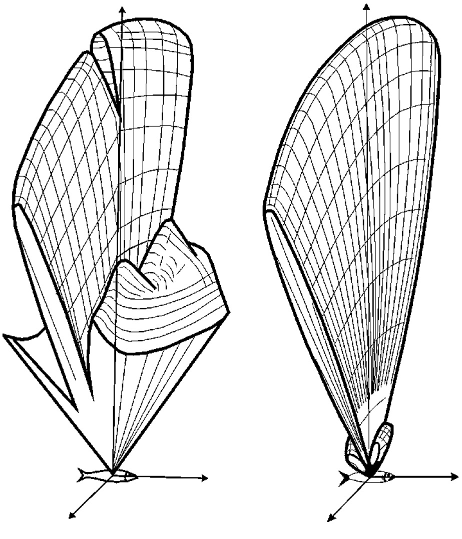

FIGURE 1.7 Spatial diagram of the sound back scattering by fish insonified in the solid angle corresponding to the sector of 35°. Left: measured at 30 kHz regarding herring 27 cm long; Right: calculated with $L_{fish}/\lambda = 5.4$.

Spatial diagrams are of great interest in the analysis of the sound scattering by fish concentrations.

The reflectivity of a fish from the dorsal aspect is complexly dependent on the direction of insonification. Figure 1.7 shows an experimentally obtained spatial diagram of the sound backscattering from fish insonified in the solid angle corresponding to the sector of 35° with $X_{fish} = 5.4$, $X_1 = 0.27$, and $X_2 = 1.08$.[19] Experimental investigations show that for some species a specific dependence of the backscattering on fish length exists. The non-identical shape of scattering diagrams of directivity relative to various species is probably explained by the variability of the exterior and the structure of fish bodies and, especially, of the volume and configuration of the swim bladder.

The dependence of the value of backscattering on the insonification angle is of practical interest. Expressed graphically, this dependence is the angular diagram of the sound backscattering by the fish obtained by averaging the results of measurements of the acoustic section over all azimuthal angles (φ) of the spatial diagram. The fish acoustic section on the axis is assumed as the initial value (θ = 0). Figure 1.8 shows such diagrams in polar coordinates.[20] The graphs characterize changes in the sound backscattered from fish, falling into the detection zone of an echo sounder, depending on the angle of their insonification (see Section 2.2).

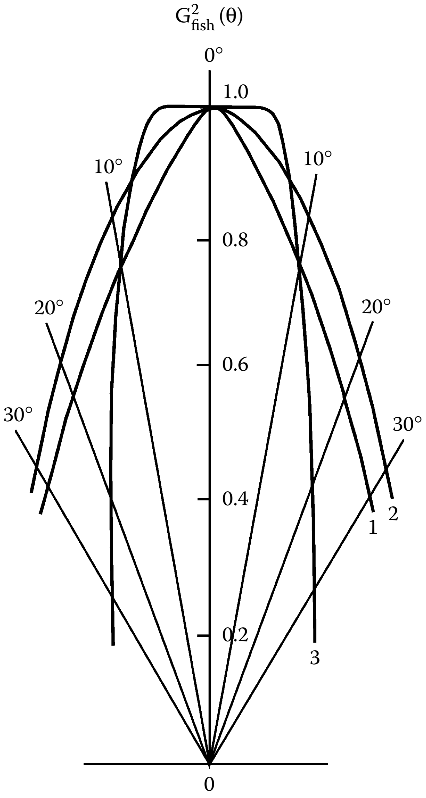

FIGURE 1.8 Average for all azimuthal angles dependences of acoustic sections of various fish on the insonification angle at 30 kHz: 1, herring 22.5 cm; 2, cod 23.5 cm; 3, flounder 22.0 cm.

The characteristic of the backscattering can be determined from the empirical formula:[19]

$$G_{fish}(\theta) = \exp\left[\left(-\frac{L_{fish}}{6\lambda}\right)\left(\sin\frac{2}{3}\theta\right)\right]^2 \qquad (1.12)$$

where $G_{fish}(\theta)$ is the characteristic (factor) directivity of backscattering of sound by fish.

Experimental investigations show that the suggested function approximates rather well the dependence of the backscattering in the dorsal aspect on the insonification angle with $\theta < 60^\circ$ and $3.0 < X_{fish} < 7.0$. As will be shown further, formula (1.12) is used in calculations of acoustic sections of concentrations, as well as in determining the detection range and zones of fish-finding instruments.

The dependence of acoustic properties of fish on frequency is of great interest. Numerous experimental measurements on fixed frequencies in the wide ultrasonic range led to the conclusion that the influence of frequency on the scattering section value is poorly pronounced. Precision frequency measurements for various species of freshwater and marine animals with the help of an experimental set within the frequency range from 20 up to 200 kHz were conducted in the laboratory and under sea conditions.[21,22]

In Figure 1.9, for instance, frequency-dependent acoustic sections are shown for marine swim bladder fish and freshwater shrimps with a dorsal aspect of insonification. The figure demonstrates that acoustic sections of fish change only slightly at comparatively low and middle frequencies ($1.5 < X_{fish} < 5.0$) but increase approximately twofold at higher frequencies ($5.0 < X_{fish} < 20$). The frequency dependence for shrimps 4.0 to 6.0 cm long has a different appearance. Within the area of values of $5.0 < X_{fish} < 7.0$, the value σ/L_p^2 on the average grows in proportion to the frequency; with $X_{fish}<1.5$, it quickly decreases at the lower frequency and with $X_{fish}<1.0$ it falls within the area of Rayleigh scattering.

Experimental studies of fish reflectivity show that the extent and pattern of scattering depend, to a large degree, on the internal structure and biometric characteristics of the fish body. Experiments on fishes conducted under laboratory and sea conditions led to the conclusion that, for commercial fish of small and middle size, when using fish-finding equipment operating at 20–30 kHz ($X_{fish} < 8.0$, $X_1 < 0.4$ and $X_2 < 1.6$), the main contribution to the acoustic section is provided by the swim bladder.[7,9] With increasing X_{fish}, X_1, and X_2 (with increasing frequency and constant fish size), the summary echo signal is formed by flesh, bone, and swim bladder signal. With still higher values of the mentioned parameters, the swim bladder signal becomes lower than that from flesh and bones.

The reflectivity of fish depends not only on their species and size but also on the depth of their habitation. The volume of a fish's swim bladder decreases with depth; therefore, the value of its acoustic section falls. The following dependence of TS in herring results from the experimental studies:[16]

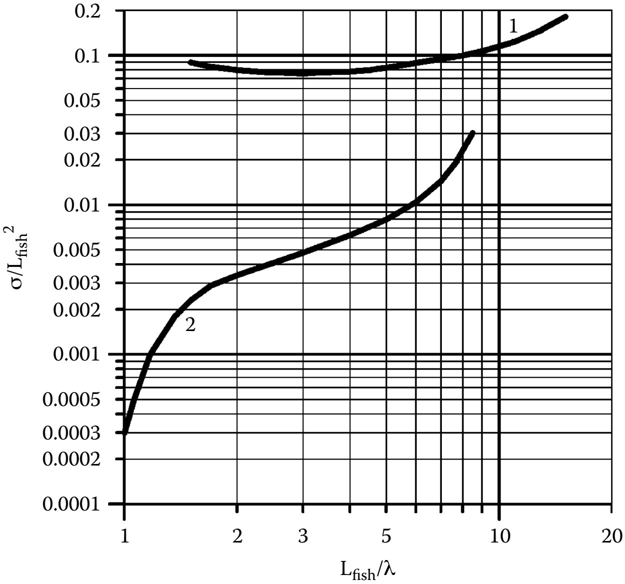

FIGURE 1.9 Frequency dependences of acoustic sections of various items: 1, fish; 2, freshwater shrimps

$$TS = 20.0\log L_{fish} - 2.3\log(1 + h/10) - 65.4 \qquad (1.13)$$

where h is the depth of habitation of fish, m.

For approximate estimation of the reflectivity of swim bladder fish, the following expression is used:[6]

$$TS = 19.1\log L_{fish} + 0.9\lambda - 23.9 \qquad (1.14)$$

This expression resulted from generalization of data of measurements of the target strength of various species in stationary conditions, recorded by a number of investigators.

With the special newly developed equipment for measuring the target strength of individual fish in the sea (see Section 5.2), more precise equations from the following studies were received for various species of commercial fish and other marine animals: blue whiting[23,24]; capelin[25,26]; sprat[27]; herring[25,28–30]; herring, sprat[31,32]; mackerel[31]; pacific whiting[33]; cod, Norway pout, redfish, great silver smelt, saithe[34]; haddock[35]; sockeye salmon[36,37]; sandeel[38]; gadoids[28]; cisco[39]; walleye pollack[40]; blue whiting, capelin, cod, haddock, herring, sea perch, mackerel, great silver smelt, saithe, shrimps, squids, jellyfish[41]; squid[42,43]; krill[44]; Arctic char, roach, perch[45]; horse mackerel[46]; jellyfish[47]; jack mackerel, Chilean and southern hake[48]; trout, roach, perch, dace, chub, carp, bleak, bream[49]; young walleye pollock[50]; sardine, anchovy[51]; redfish[52,53]; young cod[54]; salmon[55]; herring[16]; and other publications.

ANALYTICAL DETERMINATION OF ACOUSTIC CHARACTERISTICS OF FISH

As mentioned earlier, the bulk of sound energy (about 90%) at the main working frequencies of acoustic instruments (20–30 kHz) is scattered by the swim bladder of fish. The dimensions of the swim bladder are comparable with the wavelength. Since the shape of the swim bladder in most marine fish is close to a cylinder, it is possible to imitate a fish with a cylinder of dimensions equal to the dimensions of the swim bladder. The problem of determining acoustical characteristics of an elastic cylinder with an arbitrary direction of insonification was solved analytically.[1,56] It is assumed that the bladder consists of a great number of elements with dimensions much shorter than the wavelength; i.e., for the bladder $X_1 << 1.0$. Each element of the bladder scatters the incident wave according to the Rayleigh law; the value of the resulting scattered field in each point of space forms a superposition of elementary fields with account of the phase shift. As a result, the acoustic section of a swim bladder is described by the following dependence:

$$\sigma = \frac{4\pi^4 R^2 L^2}{\lambda^2} \, I_1^2 \left(\frac{4\pi R}{\lambda} \right) \tag{1.15}$$

where R is the radius of a cylinder, L is the length of a cylinder, and I_1 is the Bessel function of the first order.

Fish swim bladders have various shapes and relative dimensions. For most fish, it can be roughly assumed that the swim bladder is close to a cylinder with the following parameters[57]:

$$R = 0.025 \, L_{fish} \tag{1.16}$$

$$L = 0.24 \, L_{fish} \tag{1.17}$$

Acoustic backscattering cross section of fish is determined by substituting the relations (1.16) and (1.17) into formula (1.15). As a result, we obtain:

$$\sigma_{fish} = 0.0137 \, \frac{L_{fish}{}^4}{\lambda^2} \, I_1^2 \left(0.31 \frac{L_{fish}}{\lambda} \right) \tag{1.18}$$

The dependence of acoustic section of a fish on its length calculated from formula (1.18) is presented by a dashed line in Figure 1.4. The figure shows that with L_{fish} = 15–30 cm and λ = 5.0 cm ($3.0 < X_{fish} < 6.0$, $0.15 < X_1 < 0.3$, and $0.6 < X_2 < 1.2$), the experimental and theoretical results are close. With $L_{fish} > 40$ cm, alternation of increase and decrease in scattering occurs. This phenomenon is in conformity with the existing theory of scattering on acoustically rigid items; however, applied to the sound scattering by fish, it requires a detailed verification by experiments.

Replacing the fish with a cylinder of the same size as the swim bladder allows us to obtain the analytical expressions describing the spatial characteristic of the sound backscattering by fish.[1,56] Comparison of the calculated characteristic with the experimental one shows that in the main features they are similar (Figure 1.7). Their major differences are the nonuniformity and comparatively large value of side lobes, as well as the cavity in the main lobe of the experimental diagram. Apparently, the differences are explained by the fact that the theory takes into consideration only the backscattering by a swim bladder, ignoring the influence of the head, spine, and other fish organs.

Replacing a fish by a cylinder with corresponding properties and dimensions also makes it possible to obtain the analytical expressions describing the spatial indicatrix of sound scattering by fish.[1,56] Figure 1.10 shows the spatial indicatrix with $X_{fish} = 3.0$, $X_1 = 0.15$, and $X_2 = 0.6$. As can be seen from the figure, the indicatrix already differs from the Rayleigh in the following: ventral scattering is more prominent than dorsal, and scattering from the sides is considerably more intense than from the head or the tail. Spatial indicatrix of sound scattered by individual fish will be used in the later analysis of multiple sound scattering by fish concentrations.

In Figure 1.11, the indicatrix of sound scattering by the fish is calculated in a plane crossing the axis of the fish body and the insonification direction. The dashed line in the figure shows the indicatrix of the sound scattering by horse mackerel obtained experimentally. Both indicatrixes correspond to the above-mentioned assumptions ($X_{fish} = 3.0$, $X_1 = 0.15$, and $X_2 = 0.6$). This figure indicates that the results of theoretical calculations conform to experimental data.

It should be noted that some of the premises supporting the analytical method of determining the acoustic characteristics of bladder fish require further experimental verification, and the range of application of these premises needs to be defined more precisely. In particular, these problems include: determination of the amount of acoustic energy scattered by a swim bladder, with different values of the parameters X_{fish}, X_1, and X_2; correctness of approximation of the form of a swim bladder by a cylinder; correctness of the assumption that the scattered field may be regarded as a superposition of the elementary Rayleigh fields, etc.

Analytical expressions (1.15) were used to choose elastic cylinders as imitators of fish when simulating concentrations. Such artificial concentrations were created for studying peculiarities of sound scattering by concentrations of various densities, including coherent and multiple scattering and other phenomena.[58–60]

The theoretical investigation of the acoustic characteristics of bladderless fish entails special difficulties and is presently in its initial stage. As a fish has a very complicated configuration and internal structure, the incident waves insonify the various parts of its body at different times and at different angles. The influence of accompanying surface diffraction and interference phenomena has not been studied sufficiently.

Further experimental and theoretical investigations should strive to obtain more precise definitions of the acoustic characteristics of various marine animals. A detailed and profound analysis of these characteristics is required for more complete ascertainment of the sound scattering by commercial items regarding the different conditions of their registrations by acoustical instruments.

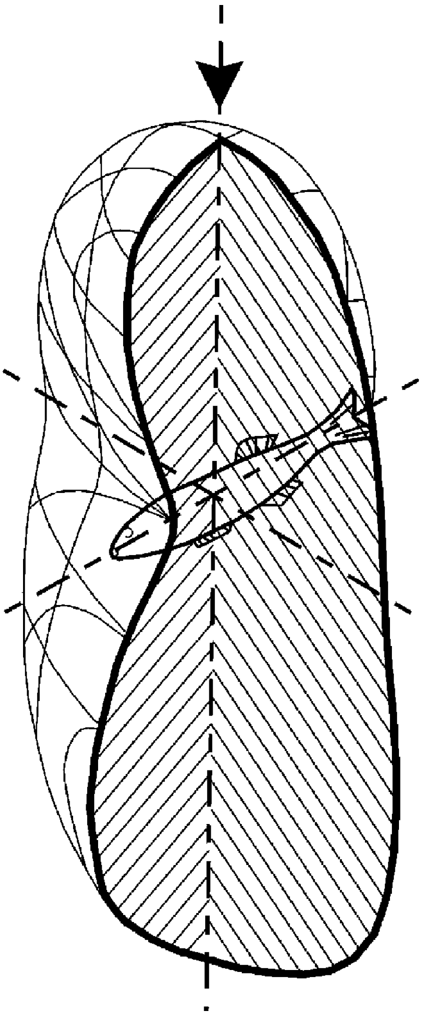

FIGURE 1.10 Spatial indicatrix of sound scattering by fish calculated with $L_{fish}/\lambda = 3.0$.

1.3 SOUND SCATTERING BY ITEM CONCENTRATIONS

When dealing with sound scattering by aquatic items, we pointed to the fact that the dimensions of a fish are usually commensurable with the acoustic wavelength. Diffraction phenomena arising from them are close to those investigated in connection with the wave propagation in turbid media.[61] In the theory of turbid media, the pattern and intensity of scattering depend not only on the acoustic properties of individual items, but also on the density of their distribution.

With insonification of concentrations where the distance between items exceeds the wavelength noticeably, the fields scattered by individual items generally do not

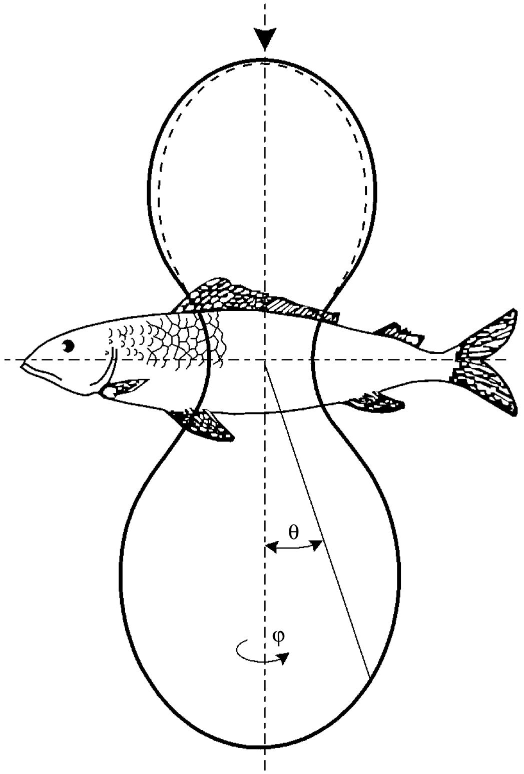

FIGURE 1.11 Plane indicatrixes of sound scattering by fish: calculated with $L_{fish}/\lambda = 3.0$ (solid line) and experimental in regard to horse mackerel 15 cm insonified at 30 kHz (dashed line).

affect each other. In this case, with a fairly wide transducer directivity diagram (which is usually typical for acoustic instruments), a number of items or even hundreds of items fall into an impulse volume, and reflections occur from all of them. With irregular distribution of aquatic items in a concentration, observed in natural conditions, the correlation of amplitudes and phases of elementary reflections varies over a wide range; therefore, the resulting amplitudes of echo signals on the transducer are occasional.

The distribution of occasional amplitudes, as well as the dependence of the intensity of echo signals on the number of insonified items, is subject to certain regularities, which were comprehensively studied by J.W. Rayleigh.[4,5] According to the Rayleigh law, the average intensity of echo signals from a concentration is equal to the sum of intensities of elementary reflections from individual fish falling into an impulse volume. Thus, the average intensity of reflected signal is in direct proportion to the number of insonified fish; i.e., to the density of the fish concentrations.

The Rayleigh regularities remain true if no fewer than seven to ten items fall into an impulse volume.[62,63] With a lower number of items in an impulse volume, the Rayleigh regularities are disturbed, and fluctuations in echo signals become even higher. In this case, considerable fluctuations occur due to a nonuniform distribution of scatterers in the detection zone of the instrument.

In dense concentrations, when the distance between neighboring items is commensurable with acoustic wavelength, the pattern of scattering is quite different. In this case, the fields scattered by individual items affect each other. In scattering the acoustic wave (scattering of the first order), each item insonifies nearby items, which also scatter part of the energy (scattering of the second order), and so on. Thus, the so-called multiple scattering phenomenon takes place.

With a fairly high concentration density, cophasal elementary reflections from individual items may be significant, which in superposition gives a regular coherent component of the resulting echo signal. Acoustic observations in the sea have shown that the signal envelope in this case cannot greatly change for a period considerably shorter than the impulse length.[63,64] Substantial changes of the envelope become possible only when the running impulse passes to a new section of the concentration, which requires a period of about the length of transmission. As a result, echo signals from dense concentrations consist of individual packets with approximately the same amplitude (Figure 1.12). The width of such packets is close to the length of the transmission. Fluctuations of such coherent echo signals are usually not great.

Let us try to make a quantitative estimation of the sound backscattering by fish concentrations of different density. As to the acoustic section, it can be easily determined in the Rayleigh scattering where the average intensity of echo signals is proportional to the number of items in an impulse volume.

THE RAYLEIGH SCATTERING OF SOUND

The simplest way of estimating the energy scattered by a concentration is with the Rayleigh law of scattering, when the average intensity of echo signals is proportional to the quantity of insonified items. Taking into account the nonuniformity of the distribution of energy in an impulse volume from the directivity of a transducer of an acoustic instrument, the acoustic section of a concentration is determined from the following relation[1]:

$$\sigma_{con} = n_{imp}\,\bar{\sigma}_{fish} = \rho_v V_{imp}\,\bar{\sigma} = \frac{c\tau}{2} r^2 \sigma_{fish} \rho_v \Psi \tag{1.19}$$

where n_{imp} is the number of items in an impulse volume, $\bar{\sigma}_{fish}$ is the acoustic section of an individual fish averaged for all fish falling into an impulse volume, ρ_v is the volume concentration density, V_{imp} is the impulse volume, c is the sound speed in water, τ is the duration of a transmitted impulse (ping), σ_{fish} is the acoustic section of fish on the axis, and Ψ is the integral directivity factor (see Section 6.1).

The acoustic section of a fish concentration characterizes the backscattering of acoustic energy, but does not allow the scattering pattern of a fish concentration to be objectively estimated. From expression (1.19), σ_{con} depends on the parameters of the acoustic instrument and the distance between it and the concentration.

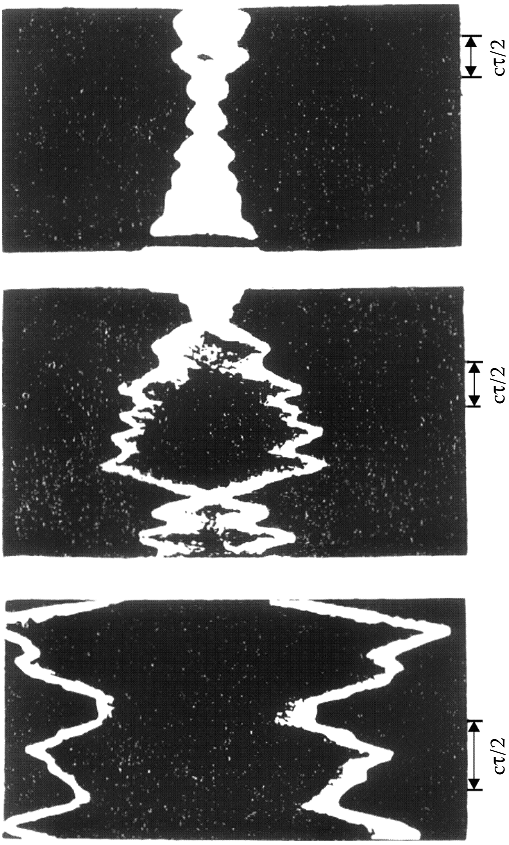

FIGURE 1.12 Echo signals from fish concentrations: from group of targets (top); Rayleigh's (middle); with signs of coherency (bottom).

To obtain an objective characteristic of the reflectivity of fish concentrations, it is expedient to use another parameter: the measure of the sound scattered by a unit volume of the concentration. This value, the so-called volume backscatter, is found from the formula:[1]

$$m_v = \rho_v \sigma_{\text{fish}} \tag{1.20}$$

The volume backscatter is the function of only the physical characteristics of a concentration; namely, the fish reflectivity and the fish density.

Tentative calculations from formula (1.20) show that the volume sound backscatter by fish concentrations can vary from 10^{-8} to 10^{-2} sp/m^3. It should be remembered that expression (1.20) is true only for concentrations of comparatively low density, which scatter sound according to the Rayleigh law. Therefore, the above range of values should be regarded as approximate.

From expressions (1.19) and (1.20), we obtain the following formula:

$$m_v = \frac{\sigma_{con}}{\left(c\,\tau/2\right)r^2\Psi} \tag{1.21}$$

The experimental verification of formula (1.21) using artificial herring concentrations of known density has given a satisfactory concurrence between theoretical and experimental results.[65]

The volume backscatter m_v is determined in cases when the value of the acoustic section of individual items forming the concentration is unknown. The reflectivity of concentrations of plankton and other small organisms, which value has not been determined, is usually estimated by m_v. The comparison of values m_v with the results of a control fishing allow measuring concentrations of plankton by the integrator readings.[66]

As a rule, to estimate commercial fish concentrations it is more suitable to use another objective characteristic of concentration reflectivity; i.e., the backscattering in terms of surface area. This is a measure of the sound backscattering by fish per unit area. It is found from the formula

$$m_s = \rho_s\sigma_{fish} = m_v h \tag{1.22}$$

where ρ_s is the area concentration density and h is the fish concentration thickness.

If no acoustic section of individual items has been measured when estimating commercial concentrations, until receiving reliable values of the acoustic section, the sound backscattering by fish per unit area is determined from formula (1.22).

The Rayleigh regularities of scattering make it possible to use another measure of the scattering properties of reflectivity of concentrations. In cases when the major aim of an acoustic survey is estimating the entire biomass of the whole length of a series of commercial items in a concentration, when determining its density, the acoustic section or target strength per one kilogram of weight is used. This value is calculated from formula (1.10).

It is expedient to use σ_{kg} and TS_{kg} for estimating the plankton biomass. As shown by experimental observations,[67] the value of TS_{kg} of an Antarctic krill concentration does not depend on its length composition: the target strength of an individual krill, as well as its mass, is approximately proportional to a specimen length raised to the third power.

It has been established that with any length composition of a krill concentration, the value TS_{kg} remains constant and equal to 38.6 dB. This value is also stable as the krill reflectivity only slightly depends on its orientation in the acoustic beam of an echo sounder. Due to the constancy of the value of TS_{kg} of krill, it became possible to estimate its density and biomass without frequent trawling for controlling the length composition of concentrations (see Section 6.2). It may be possible to estimate concentrations of the various shapes of small plankton in a similar way.

COHERENT REFLECTION OF SOUND

If the concentration is of fairly high density, the backscattered sound has a regular, coherent pattern. When calculating the degree of coherence, we will assume that the side lobes of the transducer directivity diagram are absent. The coherent component of the acoustic section, as known, is proportional to the square of the number of objects in each Fresnel zone of an impulse volume[1]:

$$\sigma_{coh} = \frac{1}{160}\pi r^4 \lambda^2 \sigma \rho_v{}^2 \Psi \theta_{eff}{}^2 \tag{1.23}$$

where θ_{eff} is the effective width of the sound beam of an acoustic instrument.*

To estimate the value of the coherent component, the coefficient of coherency is defined as:

$$K_{coh} = \frac{\sigma_{coh}}{\sigma_{ncoh}} \tag{1.24}$$

where σ_{ncoh} is the noncoherent component of acoustic section of a concentration described by formula (1.19).

Substituting (1.19) and (1.23) into (1.24), after transformations, gives:

$$K_{coh} = \frac{\pi \lambda^2 r^2 \theta_{eff}{}^2 \rho_v}{80 c\tau} \tag{1.25}$$

The discussion above shows that the reflection coherency is determined by wavelength, impulse length, acoustic beam width, concentration density, thickness, and depth. The correctness of expression (1.25) was verified on artificial model concentrations.[60] The results showed satisfactory coincidence of the experimental data with the calculated ones. Let us assume scattering with $K_{coh} < 0.1$ to be noncoherent (Rayleigh's), while scattering with $K_{coh} > 10$ to be completely coherent.

Using expression (1.25), we have calculated the coefficient of coherency for an EK60 Scientific Sounder System in regard to various concentration densities, thickness, and depths (Figure 1.13). As can be seen in the graphs, when locating a concentration with a typical low-frequency instrument, coherent scattering can be considerable with concentrations of high density, even if they are located at comparatively shallow depth. For example, with depth $r_{con} = 400$ m, thickness $h = 25$ m, and $X_4 = 19$, echo signal coherency becomes noticeable ($K_{coh} = 1.0$) if density $\rho_v = 1.0$ sp/m^3; i.e., $X_3 = 14$. The coherency of the scattered field diminishes with decreasing concentration thickness. With the use of a high-frequency echo sounder

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* The maximal width within which an item is registered by an instrument is referred to as the effective width of the beam.

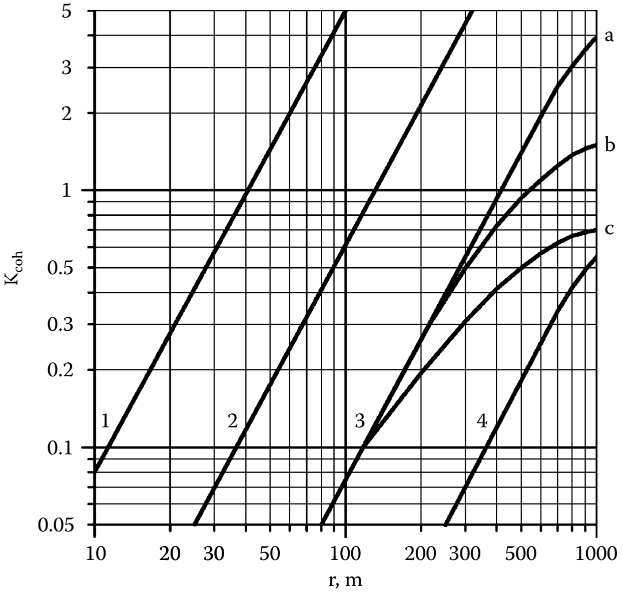

FIGURE 1.13 Dependence of coherency coefficient on the distance to fish concentrations of various thicknesses and densities when registered by an EK60 Scientific Sounder System operating at 38 kHz (λ = 3.95 cm, τ = 1.0 ms): 1, ρ_v = 100 sp/m^3; 2, ρ_v = 10 sp/m^3; 3, ρ_v = 1.0 sp/m^3 (a, h = 25 m; b, h = 10 m; c, h = 5.0 m); 4, ρ_v = 0.1 sp/m^3.

or sonar with a long impulse, the contribution of the reflection coherency noticeably decreases.

In the above-mentioned discussion, we did not take into consideration the effect of sound scattering by the heterogeneities of the sea. However, various organic and nonorganic inclusions occurring in the sea as well as heterogeneities occurring in the microstructure of the water may give rise to additional fluctuations of echo signals and decrease the influence of the reflection coherency. Taking this into account, the above preliminary estimation of coherent scattering must be verified and defined more precisely by experiments.

MULTIPLE SCATTERING OF SOUND

In very dense concentrations, in addition to coherent reflection, one should also take into account multiple sound scattering.[1] The intensity of multiple scattering changes with the propagation of the acoustic wave in the concentration: at first multiple scattering increases, reaches a certain maximum, and then begins to decrease. Penetrating into a dense concentration, the acoustic wave first undergoes first-order scattering when the resulting echo signal is composed of elementary reflections from individual items in an impulse volume. Having penetrated the concentration, the acoustic wave scattered by individual items insonifies other items and these in turn insonify other items, and so on. With considerable density, multiple scattering (of the second and higher orders) can be great.

Let us try to clarify the conditions under which multiple sound scattering in fish concentrations becomes considerable. In the theory of light scattering in a turbid medium, one of the most important characteristics of the medium is its optical thickness.[61] The length of the path of the beam in the medium along which its intensity decreased "e" times is taken as a unit of optical thickness equal to one Rayleigh. Optical thickness can be expressed in the dimensionless parameters of the scattering medium

$$\delta_{opt} = \frac{X_2^2 X_4}{X_3^3} \tag{1.26}$$

With consideration of the fact that acoustic wave phenomena are similar to optical ones, expression (1.26) can be applied to multiple sound scattering. Substituting formulas (1.3), (1.4), and (1.5) and the values L_2, L_3, and L_4 obtained in the vertical location into expression (1.26) gives the following formula for the acoustic thickness of a fish concentration:

$$\delta_{ac} = 0.12 c \tau \rho_v L_{fish}{}^2 \tag{1.27}$$

From expression (1.27) it follows that the acoustic thickness of the fish concentration rises with increasing duration of acoustical impulses penetrating therein, the fish density, or the fish size.

From the theory of scattering in turbid media, it follows that with $\delta_{ac} < 0.1$ Rayleigh, multiple scattering can be neglected; with 0.1 Rayleigh < δ_{ac} <0.3 Rayleigh, an adjustment for scattering of the second order needs to be made; and with $\delta_{ac} > 0.3$ Rayleigh, the whole complex of effects of multiple scattering becomes important.

Figure 1.14 shows the results of calculating the acoustic thickness of fish concentrations of various densities with application of echo sounders operating at different frequencies. As can be seen from the graphs, when using low-frequency echo sounders, multiple scattering should be expected in very dense fish concentrations only (when $X_3 < 3.0$). In cases where high-frequency echo sounders are used, multiple scattering is scarcely probable. The colossal densities required for this are perhaps possible in concentrations of plankton organisms or krill.

The above considerations were verified experimentally on artificial model concentrations.[58] The experimental data conformed well to the calculated ones. With the use of a low-frequency acoustic instrument (operation frequency 30 kHz and impulse duration $\tau = 1.0$ ms), multiple scattering became noticeable with the concentration density of small fish ($L_{fish} = 8.0$ cm^2) higher than 120 sp/m^3; i.e., with $\delta_{ac} = 0.15$ Rayleigh (with $X_3<2.0$, $X_4 = 15$).

It has been shown by empirical investigations that multiple scattering increases the duration and decreases the intensity of echo signals without changing their energy.[1] Therefore, multiple scattering should not influence the result of echo integration and estimating the density of commercial concentrations. However, an

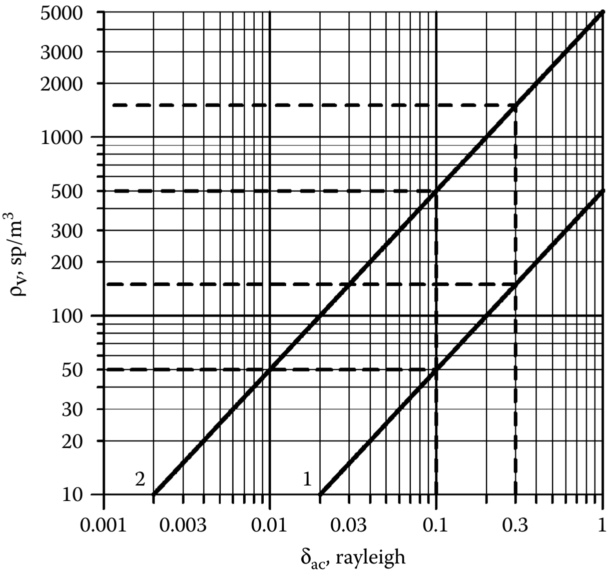

FIGURE 1.14 Dependence of acoustic thickness of the concentration of fish (L_{fish} = 10 cm) on the density when using echo sounders operating at various frequencies: 1, 20–30 kHz, τ = 1.0 ms; 2, 120–200 kHz, τ = 1.0 ms.

increase in duration of echo signals leads to distorting the dimensions of concentrations registered by acoustic instruments.

It should also be taken into account that, as sound waves penetrate into the depth of a dense concentration, additional decrease in their intensity occurs because of the attenuation of the energy by the thickness of concentration.[68] This is accounted for by the fact that, with multiple scattering, acoustic waves have to pass longer distances inside concentrations and undergo multiple attenuation within fish themselves. It is natural that with coherent and multiple scattering as well as with the attenuation of sound in a water-fish medium, the proportionality between concentration density and echo signal intensity breaks down. The establishment of the dependence of echo signal intensity on the degree of concentration in dense schools of marine items requires further theoretical and experimental investigations.

1.4 CLASSIFICATION OF ECHO SIGNALS FROM COMMERCIAL ITEMS

Echo signal intensities, the degree of their fluctuations, as well as the character of representing concentrations when registered by acoustic instruments depends to a great extent upon the number of commercial items in an impulse volume. This number can be found from the following relation[69]:

$$n_{item} = V_{imp}\rho_v = \frac{1}{8}\,\pi\theta_{eff}{}^2 c\tau r^2 \rho_v \qquad (1.28)$$

where V_{imp} is an impulse volume.

As follows from relation (1.28), the number of items in an impulse volume depends upon the concentration density, the parameters of the fish-finding instrument, and the distance to concentration.

If, when detecting a concentration, no more than one item simultaneously falls in an impulse volume, echo signals from individual targets come to the point of reception; the envelope of such a signal has a smooth shape and the length of about the duration of a transmission. For convention's sake, let us call echo signals from individual items *elementary* ones. An acoustic instrument registers such echo signals separately.

If several or even hundreds of items fall into an impulse volume ($X_3 >> 1.0$), echo signals from them represent the sum of elementary reflections from separate specimens. In this case, as mentioned in the previous section, the dependence of the intensity of echo signals on the number of insonified items is subject to regularities adequately studied by J.W. Rayleigh. According to the Rayleigh dependence, the value of the average intensity of echo signals is proportional to the number of items in an impulse volume.

The Rayleigh regularities of scattering are true if no fewer than seven to ten items fall into an impulse volume.[62,63] Let us call echo signals, which are subjected to the Rayleigh regularities, *Rayleigh* ones. The envelope of Rayleigh echo signals has an abrupt character, strongly fluctuating from transmission to transmission (Figure 1.12).

With a lower number of items in an impulse volume, the Rayleigh regularities are disturbed, and fluctuations in echo signals become even higher. In this case, considerable fluctuations occur due to a nonuniform distribution of scatterers in the detection zone of an instrument (see Section 2.2). Let us call echo signals from a comparatively small number of items, *group* ones. Group signals represent series of elementary ones, overlapping each other (Figure 1.12).

The Rayleigh regularities of echo signal scattering are also disturbed with a considerable number of items in an impulse volume, when the distance between neighboring items are commensurable with the acoustic wavelength. As mentioned in the previous section, with a high enough concentration density, the resulting echo signals have a regular, coherent component. The degree of coherency depends upon the concentration density and the sizes of the Fresnel zones. The relation between the coherent and noncoherent echo signals is determined by the coefficient of coherency K_{coh}. In this case, the number of items in an impulse volume is found from the following formula:[1]

$$n_{item} = 10K_{coh}\left(\frac{c\tau}{\lambda}\right)^2 \qquad (1.29)$$

As already mentioned, an echo signal is considered as a noncoherent (Rayleigh's) with $K_{coh}<0.1$ and completely *coherent* with $K_{coh}>10$. If the coefficient of coherency has an intermediate value, an echo signal includes both coherent and noncoherent components. Let us call such an echo signal *complex*.

Acoustic observations in the sea have shown that the signal envelope cannot greatly change for a period considerably shorter than the insonifying impulse length.[64] Significant changes of the envelope become probable only when the running impulse passes to a new section of the concentration, which requires a period of about the length of a transmission. As a result, coherent echo signals from dense concentrations consist of individual packets with approximately the same amplitude (Figure 1.12). The width of such packets is close to the length of a transmission; however, their shape differs substantially from the envelope of a transmission. Fluctuations of such coherent echo signals are usually not great.

Thus, echo signals can be classified as elementary, group, Rayleigh's, complex, or coherent, depending on the number of items falling into an impulse volume.

Taking into account the established limiting values of the number of items in an impulse volume, it is possible to determine from formulas (1.28) and (1.29) the corresponding limiting values of the concentration density. In Table 1.2, the expressions for determining limiting values of concentration density are given with respect to echo signals of varying types.

The limiting values of concentration density for an EK60 Scientific Sounder System and depth of 200 m are given below. Substituting initial values for the low frequency ($f = 38$ kHz, $\lambda = 3.95$ cm, $\tau = 1.5$ m, $\theta_{eff} = 7^\circ$) and for the high frequency ($f = 120$ kHz, $\lambda = 1.25$ cm, $c\tau = 0.375$ m, $\theta_{eff} = 7^\circ$) into the expressions given in the table, we obtain the following limit values of the fish concentration density (Table 1.3).

The results of calculations show that with registering the concentration by an EK60 instrument, the limiting values can differ by several orders. Therefore, the character of echo signals from concentrations may vary over great ranges depending on the parameters of the acoustic instrument. This thesis is well illustrated by the graph in Figure 1.15. The graph presents the dependence of the number of impulses in an impulse volume upon distance, calculated for registration of sufficient dense concentration by an EK60. The limiting values of the number of fish for each type of echo signal are marked. The graph shows that, for example, the low frequency

TABLE 1.2
Limiting conditions for echo signals of various types

Type of Echo Signal	Number of Items in an Impulse Volume	Limiting Concentration Density
Elementary	$n_{item} < 1$	$8(\pi\theta_{eff}^2 c\tau r^2)c^{-1}$
Group	$1 < n_{item} < 10$	$80(\pi\theta_{eff}^2 c\tau r^2)^{-1}$
Rayleigh's	$10 < n_{item} < (c\tau/\lambda)^2$	$8c\tau(\pi\theta_{eff}^2\lambda^2 r^2)^{-1}$
Complex	$(c\tau/\lambda)^2 < n_{item} < (10c\tau/\lambda)^2$	$800c\tau(\pi\theta_{eff}^2\lambda^2 r^2)^{-1}$
Coherent	$n_{item} > (10c\tau/\lambda)^2$	

TABLE 1.3
Limiting concentration density

Frequency (kHz)	Echo Signal Type	Density (sp/m^3)
38	Elementary	0.0029
	Group	0.029
	Rayleigh's	4.3
	Complex	430
120	Elementary	0.012
	Group	0.12
	Rayleigh's	10.7
	Complex	1070

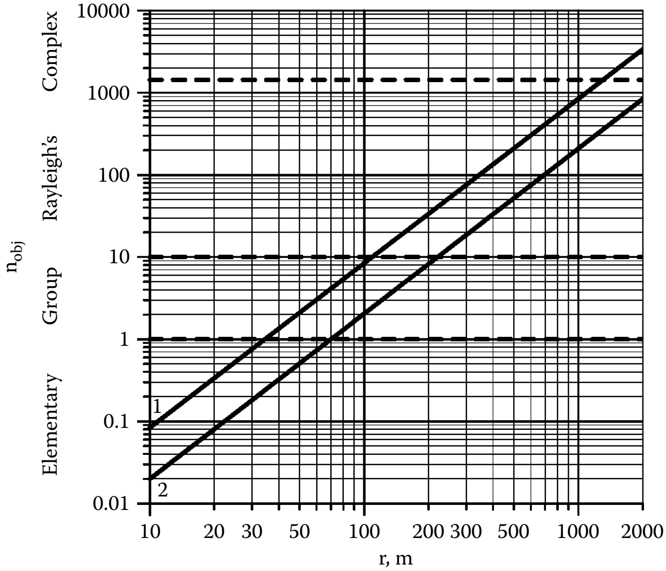

FIGURE 1.15 Dependence of the number of fish in the impulse volume on the distance to the fish concentration (ρ_v = 0.1 sp/m^3) when registered by an EK60 Scientific Sounder System operating at various frequencies: 1, 38 kHz; 2, 120 kHz.

tract will register the concentration at a depth of 200 m as Rayleigh's signals and, at the same time, the high-frequency tract will record the same concentration as group signals.

The echo signal type, to a great extent, also depends on the distance to concentration. The graph also demonstrates that with the low frequency tract operating on concentrations of the same density but situated at shallower depths, the echo signals may appear as elementary or group signals, at mid-depths as Rayleigh's signals, and at greater depths as complex signals.

Thus, the suggested classification of echo signal is based on peculiarities of the sound scattering with various distributions of items in an impulse volume of a fish-finding instrument. All types of echo signals received from concentrations differ with the structure, the character of changing the intensity, and fluctuations. This fact should be taken into account when detecting and interpreting the readings of acoustic instruments.

1.5 STATISTICAL PROPERTIES OF ECHO SIGNALS FROM COMMERCIAL ITEMS

The efficiency of detecting echo signals from commercial items is determined by the minimal intensity of echo signals required for their registration by the receiver against a background of disturbances. The minimal or threshold intensity of echo signals I_s is usually compared with the level of acoustic noises I_n through the coefficient of recognition δ_s. The latter is characterized by the acoustic pressure of a useful signal to that of a noise at the point of reception, with which it is possible to detect the signal against the background of disturbance:

$$I_s = \delta_s^2 I_n \tag{1.30}$$

As follows from this simple relation, the admissible minimal intensity of useful signals depends on the level of acoustic noises and the coefficient of recognition.

Reducing the level of noise of a vessel is usually achieved by its suppression where it is being generated. It is also possible to reduce the level of noises through the narrowing of the frequency band of a receiver or the use of a narrow-beam transducer. Lowering of the coefficient of recognition with reverberation noises is achieved by using correlation methods for treating signals in receiver systems. The cited methods of suppressing disturbances allow for decreasing the level of noises and, thus, increasing the efficiency of the work of acoustic instruments. However, the mentioned measures may not suffice to ensure reliable detection of echo signals from commercial items, especially at great depths.

In analyzing the possibilities of lowering the coefficient of recognition, it is necessary to take into account that both useful and noisy signals are fluctuating by nature. It is known from statistic radar theory that the distribution density of probability of instantaneous intensities for signals of this kind is described by the exponential law[70]

$$F(I_i) = 1/\bar{I}\ \exp\left(-I_i/\bar{I}\right) \tag{1.31}$$

where $\bar{I}$ is the average intensity of signals.

The probability of the fact that in the receiver input with the real sensibility

$$I_s = \bar{I}$$

instantaneous intensities of reflected signals exceed the noises I_n

$$p(I_i > I_n) = \int_{I_n}^{\infty} 1/I_s \exp(-I_i/I_s) dI_i = \exp(-I_n/I_s) \tag{1.32}$$

On the other hand, expression (1.31) can be represented as

$$p(I_i > I_n) = n_i/n \tag{1.33}$$

where n_i is the number of independent samples, the intensity of which exceeds I_n and n is the general number of echo signals.

Uniting (1.32) and (1.33), after transformations, we obtain:

$$\delta_s^2 = I_s/I_n = \frac{0.43}{\log\left(n / n_i\right)} \tag{1.34}$$

It follows from relation (1.34) that it is possible to decrease the coefficient of recognition by increasing the frequency of repetition of echo signals and length of observation.

Lowering of the detecting threshold also can be achieved by using more sophisticated methods of treating the acoustic information received. We would like to demonstrate that, in order to decrease the coefficient of recognition δ_s, it is practical to use the method of accumulation and averaging of echo signals, which is widely applied in radar of meteorological formations.

As follows from the theory of radar,[71] with n > 9

$$\delta_s^2 = 2 / \left(\sqrt{n} - 1\right)^{-1} \tag{1.35}$$

with a probability of 98%. For instance, with the number of echo signals n = 100, accumulation and averaging of signals ensure a coefficient of recognition $\delta_s = 0.45$.

Experimentally established or calculated with the help of relation (1.35), admissible values of the coefficient of recognition may be ensured by various technical means. As known from the theory of radar,[72]

$$\delta_s^2 = \frac{2\, K_\delta^2}{\tau\, \Delta f} \tag{1.36}$$

where K_δ is the coefficient of reliability of reception, that is, the minimally required relation of a signal to a disturbance at the indicator input; τ is the time of averaging of a signal, equal to the locating impulse duration; and Δf is the frequency band of a receiving tract.

It appears from relation (1.36) that the value of the coefficient of recognition depends on the frequency band of the receiver and the duration of locating impulses; the δ_s value depends on the operator qualification and the indicator type as well.

In registering a commercial target on the tape of a recorder or the screen of an electronic indicator, when echo signals are marked by parallel tracks, the readability of the image improves as the number of the signal increases. The ability to detect also depends on their shape and size on the indicator; by increasing patch size, the readability improves.

Figure 1.16 presents the dependence of the coefficient K_δ^2 on the number of echo signals with which it is possible to recognize the image of a target on a recorder tape against the background of disturbances.[73] The graph demonstrates that, if more than five echo signals come from an individual target while a vessel is in motion, then $K_\delta^2 = 1.2$. Using relation (1.36) for $\Delta f = 1.2$ kHz and $\tau = 1.0$ ms, we obtain $\delta_s = 1.4$. With an immovable vessel, when more than 25 signals come from the target, $K_\delta^2 = 0.5$ and $\delta_s = 0.9$.

Due to the inculcation of digital technique, processor treatment of echo signals finds wide application in fish-finding instruments. The property of synchronous repetition of echo signals from targets with a random character of noises and reverberation disturbance is used. The signal is memorized for a sequence of transmissions in the block of memory and then it is summed up. When summing, the amplitude of useful signals due to the synchronism increases n times, while the amplitude of noises rises $\sqrt{n}$ times only (because of their random nature).

The summary signal is then divided by the number of transmissions. As a result, the amplitude of useful echo signals keeps its initial value, while the level of disturbances considerably decreases (Figure 1.17).

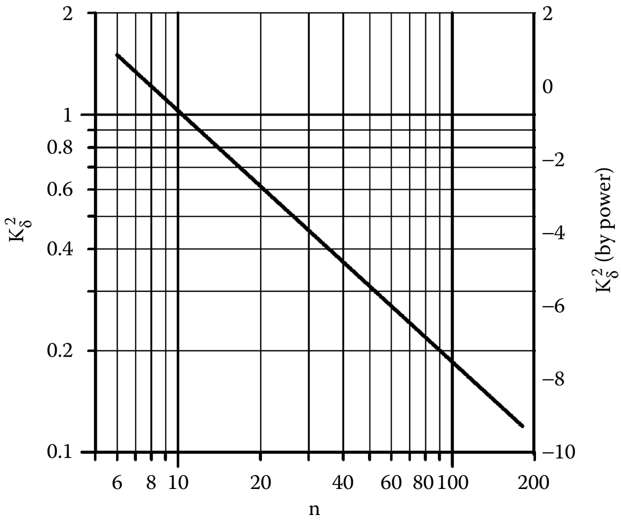

FIGURE 1.16 Dependence of the coefficient of reliability of reception (K_δ) on the number of echo signals from the target on the printer paper (n).

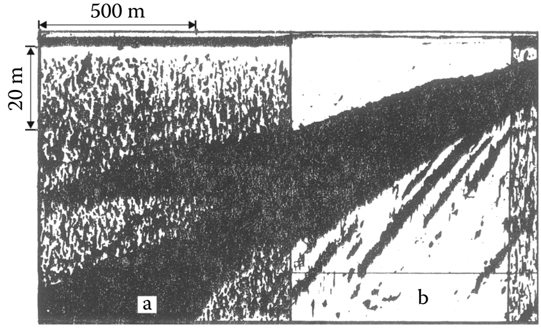

FIGURE 1.17 The echogram illustrating the suppression of disturbances (range 75 m): a, the suppression device is switched off; b, the suppression device is switched on.

Substantial increase in the range of detection of commercial items can also be achieved through the use of modulated by frequency, phase, or amplitude impulses of long duration with a resulting temporal compressing of received signals. The insonification of impulses of long duration and internal modulation ensure an increase of the detection range, while the use of the compression of echo signals allows obtaining the high resolution of the equipment. Unfortunately, this perspective method has so far found a limited application because of the difficulties in treating the information received.

REFERENCES

1. Yudanov, K.I. and Kalikhman, I.L., Sound scattering by marine animals, in Meeting on Hydroacoustical Methods for the Estimation of Marine Fish Populations, 25–29 June 1979, II: Contributed Papers, Discussions, and Comments, Suomala, J.B., Ed., The Charles Stark Draper Laboratory, Cambridge, MA, 53, 1981.
2. Lozov, J.B. and Suomala, J.B., *The Application of Hydroacoustical Methods for Aquatic Biomass Measurements*, The Charles Stark Draper Laboratory, Cambridge, MA, 60, 1971.
3. MacLennan, D.N. and Simmonds, E.J., *Fisheries Acoustics*, Chapman & Hall, London, 325, 1992.
4. Rayleigh, J.W.S., *Treatise on the Theory of Sound*, Macmillan, London, 1877.
5. Rayleigh, J.W., *The Theory of Sound*, Vols. 1 and 2, Dover, New York, 1945.
6. Love, R.H., Dorsal-aspect target strength of an individual fish, *Journal of the Acoustical Society of America*, 49(3), 816, 1971.
7. McCartney, B.S. and Stubbs, A.R., Measurements of the acoustic target strength of fish in dorsal aspect, including swimbladder resonance, *Journal of Sound and Vibration*, 15(3), 7, 1971.
8. Yudanov, K.I., *Interpretation of Echograms of Hydroacoustic Fish-Finding Instruments*, Vilim, E., Trans., Keter Press, Jerusalem, 101, 1971.
9. Samovol'kin, V.G., Acoustical baskscattering cross section of small fish, crustaceans, and medusae as function of their foreshortening, *Oceanology*, 14(5), 655, 1974 (translated from Russian).

10. Holliday, D.V., The use of swimbladder resonance in the sizing of schooled pelagic fish, in Hydro-Acoustics in Fisheries Research, A Symposium Held in Bergen, 19–22 June 1973, Margetts, A.R., Ed., *Rapports et Proces-Verbaux des Reunions*, 170, 130, 1977.
11. Nakken, O, and Olsen, K., Target strength measurements of fish, in Hydro-Acoustics in Fisheries Research, A Symposium Held in Bergen, 19–22 June 1973, Margetts, A.R., Ed., *Rapports et Proces-Verbaux des Reunions*, 170, 52, 1977.
12. Dawson, J.J. and Karp, W.A., *In situ* measures of target-strength variability of individual fish, in Developments in Fisheries Acoustics, A Symposium Held in Seattle, 22–26 June 1987, Margetts, A.R., Ed., *Rapports et Proces-Verbaux des Reunions*, 189, 264, 1990.
13. Hewitt, R.P. and Demer, D.A., Lateral target strength of Antarctic krill, in Fisheries and Plankton Acoustics, Proceedings of an ICES International Symposium Held in Aberdeen, Scotland, 12–16 June 1995, Simmonds, E.J. and MacLennan, D.N., Eds., *ICES Journal of Marine Science*, 53(2), 297, 1996.
14. MacLennan, D.N. and Menz, A., Interpretation of *in situ* target strength data, in Fisheries and Plankton Acoustics, Proceedings of an ICES International Symposium Held in Aberdeen, Scotland, 12–16 June 1995, Simmonds, E.J. and MacLennan, D.N., Eds., *ICES Journal of Marine Science*, 53(2), 233, 1996.
15. Rose, G.A. and Porter, D.R., Target-strength studies on Atlantic cod (*Gadus morhua*) in Newfoundland waters, in Fisheries and Plankton Acoustics, Proceedings of an ICES International Symposium Held in Aberdeen, Scotland, 12–16 June 1995, Simmonds, E.J. and MacLennan, D.N., Eds., *ICES Journal of Marine Science*, 53(2), 259, 1996.
16. Ona, E., An expanded target-strength relationship for herring, in Acoustics in Fisheries and Aquatic Ecology, Part 1: Proceedings of an ICES Symposium Held in Montpellier, France, 10–14 June 2002, MacLennan, D.N., Ed., *ICES Journal of Marine Science*, 60(3), 493, 2003.
17. Ermolchev, V.A. and Zaferman, M.I., Results of experiments on the video-acoustic estimation of fish target-strength *in situ*, in Acoustics in Fisheries and Aquatic Ecology, Part 1: Proceedings of an ICES Symposium Held in Montpellier, France, 10–14 June 2002, MacLennan, D.N., Ed., *ICES Journal of Marine Science*, 60(3), 544, 2003.
18. Yudanov, K.I., *Acoustic Fisheries Prospecting*, Sudostroenie, Saint-Petersburg, 187, 1992 (in Russian).
19. Yudanov, K.I., Kalikhman, I.L., Gankov, A.A., and Shatoba, O.E., Sound scattering by commercial fish, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series "Fishery Acoustic Problems," Yudanov, K.I., Kalikhman, I.L., Shabalin, V.N., Eds., VNIRO, Moscow, 7, 1983 (in Russian).
20. Yudanov, K.I., Reflective power of commercially important fishes and fish concentrations, in Hydro-Acoustics in Fisheries Research, A Symposium Held in Bergen, 19–22 June 1973, Margetts, A.R., Ed., *Rapports et Proces-Verbaux des Reunions*, 170, 185, 1977.
21. Samovol'kin, V.G., Apparatus and experimental technique for the study of ultrasonic backscattering by biological objects in water, *Oceanology*, 14(1), 149, 1974 (translated from Russian).
22. Samovol'kin, V.G., Back ultrasound scattering by fish and shrimps, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series "Fishery Acoustic Problems," Yudanov, K.I., Kalikhman, I.L., Tesler, W.D., Kamenskaya, E.A., Eds., VNIRO, Moscow, 26, 1981 (in Russian).

23. Robinson, B.J., An *in situ* technique to determine fish target strength with results for blue whiting *Micromesistius poutassou* (Risso), *Journal du Conseil Permanent International pour l'Exploration de la Mer*, 40, 153, 1982.
24. Forbes, S.T., Progress in dual-beam target strength measurement on herring and blue whiting, presented at International Council for the Exploration of the Sea, Copenhagen, Denmark CM 1985/B:22, 5, 1985 (mimeo).
25. Halldorsson, O. and Reynisson, P., Target strength measurement of herring and capelin *in situ* at Iceland, *FAO Fisheries Report*, 300, 78, 1983.
26. Rose, G.A. and Leggett, W.C., Hydroacoustic signal classification of fish schools by species, *Canadian Journal of Fisheries and Aquatic Sciences*, 45, 597, 1988.
27. Robinson, B.J., *In situ* measurements on the target strength of pelagic fishes, *FAO Fisheries Report*, 300, 99, 1983.
28. Foote, K.G., Fish target strength for use in the echo integrator surveys, *Journal of the Acoustical Society of America*, 88, 1543, 1987.
29. Rudstam, L.G., Lindem, T., and Hansson, S., Density and *in situ* target strength of herring and sprat: A comparison between two methods of analysing single-beam sonar data, *Fisheries Research*, 6, 305, 1988.
30. Misund, O.A. and Øvredal, J.T., Acoustic measurements of schooling herring: estimation of school biomass and target strength, presented at International Council for the Exploration of the Sea, Copenhagen, Denmark CM 1988:B/26, 16, 1988 (mimeo).
31. Edwards, J.I., Armstrong, F., Magurran, A.E., and Pitcher, T.J., Herring, mackerel and sprat target strength experiments with behavioural observations, presented at International Council for the Exploration of the Sea, Copenhagen, Denmark CM 1984/B:34, 21, 1984 (mimeo).
32. Degnbol, P., Lassen, H., and Staehr, K.J., *In situ* determination of target strength of herring and sprat at 38 and 120 kHz, *Dana*, 5, 45, 1985.
33. Williamson, N.J. and Traynor, J.J., *In situ* target strength estimation of Pacific whiting (*Merluccius productus*) using a dual-beam transducer, *Journal du Conseil Permanent International pour l'Exploration de la Mer*, 41, 285, 1984.
34. Foote, K.G., Aglen, A., and Nakken, O., Measurement of fish target strength with a split-beam echo sounder, *Journal of the Acoustical Society of America*, 80, 612, 1986.
35. Ona, E. and Nansen, K., *In situ* target strength observations on haddock, presented at International Council for the Exploration of the Sea, Copenhagen, Denmark CM 1986/B39, 13, 1986 (mimeo).
36. Burczynski, J.J. and Johnson, R.L., Application of dual-beam acoustic survey technique to limnetic population of juvenile sockeye salmon *Oncorhynchus nerka*, *Canadian Journal of Fisheries and Aquatic Sciences*, 43, 1776, 1986.
37. Mulligan, T.J. and Kieser, R., Comparison of acoustic population estimates of salmon in a lake with a weir count, *Canadian Journal of Fisheries and Aquatic Sciences*, 43, 1373, 1986.
38. Armstrong, F., Target strength of sand eels, presented at International Council for the Exploration of the Sea, Copenhagen, Denmark CM 1986/B:5, 6, 1986 (mimeo).
39. Rudstam, L.G., Clay, C.S., and Magnuson, J.J., Density and size estimates of cisco (*Coregonus artedi*) using analysis of peak PDF from a single-transducer sonar, *Canadian Journal of Fisheries and Aquatic Sciences*, 44, 811, 1987.
40. Foote, K.G. and Traynor, J.J., Comparison of walleye pollack target strength estimates determined from *in situ* measurements and calculations based on swimbladder form, *Journal of the Acoustical Society of America*, 83, 9, 1988.

41. Mamylov, V.S., Results of estimating target strength *in situ* at frequency of 38 kHz for the main commercial items of North Atlantic, Instrumental Methods of Estimating the Stocks of Commercial Items, Polar Research Institute of Marine Fisheries and Oceanography (PINRO) and All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), Collected Scientific Papers, PINRO, Murmansk, USSR, 3, 1988 (in Russian).
42. Jefferts, K., Burczynski, J.J., and Pearcy, W.G., Acoustical assessment of squid *Loligo opalescens* off the central Oregon coast, *Canadian Journal of Fisheries and Aquatic Sciences*, 44, 1261, 1987.
43. Arnaya, I.N., Sano, N., and Iida, K., Studies on acoustic target strength of squid III: Measurement of the main target strength of small live squid, *Bulletin of the Faculty of Fisheries, Hokkaido University*, 40(2), 100, 1989.
44. Foote, K.G., Everson, I., Watkins, J.L., and Bone, D.G., Target strength of Antarctic krill (*Euphausia superba*) at 38 and 120 kHz, *Journal of the Acoustical Society of America*, 87, 16, 1990.
45. Dziedzic, A., Chorier, C., Dubois, J.P., and Vray, D., Broadband Target-Strength Functions of Three Species of Fresh Water Free-Swimming Fish, presented at ICES International Symposium Held in Aberdeen, Scotland, 12–16 June 1995.
46. Cordova, J. and Paillaman, A., Horse Mackerel (*Trachurus symmetricus murphyi*), Target-Strength (TS) Estimation, presented at ICES International Symposium Held in Aberdeen, Scotland, 12–16 June 1995.
47. Mutlu, E., Target strength of the common jellyfish (*Aurelia aurita*): A preliminary experimental study with a dual-beam acoustic system, in Fisheries and Plankton Acoustics, Proceedings of an ICES International Symposium Held in Aberdeen, Scotland, 12–16 June 1995, Simmonds, E.J. and MacLennan, D.N., Eds., *ICES Journal of Marine Science*, 53(2), 309, 1996.
48. Lillo, S., Cordova, J., and Paillaman, A., Target-strength measurements of hake and jack mackerel, in Fisheries and Plankton Acoustics, Proceedings of an ICES International Symposium Held in Aberdeen, Scotland, 12–16 June 1995, Simmonds, E.J. and MacLennan, D.N., Eds., *ICES Journal of Marine Science*, 53(2), 267, 1996.
49. Kubecka, J. and Duncan, A., Acoustic versus real size relationships for common species of riverine fish, *Fisheries Research*, 35(1–2), 115, 1998.
50. Iida, Kohji, Mukai, Tohru, Mori, and Hideki, Frequency characteristics of acoustic volume backscattering strength of sound scattering layer and estimation of target strength of constituent organisms, *Bulletin of the Japanese Society of Scientific Fisheries*, 65(1), 66, 1999.
51. Machias, A., Giannoulaki, M., Somarakis, S., Koutsikopoulos, C., Manoussakis, A., Kapantagakis, A., and Tsimenides, N., *In situ* estimation of sardine and anchovy target strength, in 6th Hellenic Symposium on Oceanography and Fisheries, Chios, Greece, 23–26 May 2000, *Proceedings*, 2, 180, 2000.
52. Gauthier, S. and Rose, G.A., Target strength of encaged Atlantic redfish (*Sebastes* spp.), *ICES Journal of Marine Science*, 58(3), 562, 2001.
53. Gauthier, S. and Rose, G.A., *In situ* target strength studies on Atlantic redfish (*Sebastes* spp.), *ICES Journal of Marine Science*, 59(4), 805, 2002.
54. Chu, D., Wiebe, P.H., Copley, N.J., Lawson G.L., and Puvanendran, V., Material properties of North Atlantic cod eggs and early-stage larvae and their influence on acoustic scattering, *ICES Journal of Marine Science*, 60(3), 508, 2003.
55. Fleischman, S.J. and Burwen, D.L., Mixture models for the species apportionment of hydroacoustic data, with echo-envelope length as the discriminatory variable, *ICES Journal of Marine Science*, 60(3), 592, 2003.

56. Kalikhman, I.L., Sound scattering by fish and imitators of fish, Scientific proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series "Progress in Fishing Technique," Treschov, A.I., Karpenko, E.A., Stepanov, G.N., Kamenskaya, E.A., Eds., VNIRO, Moscow, 83, 1978 (in Russian).
57. Nakken, O. and Olsen, K., Target strength measurements of fish, in Hydro-Acoustics in Fisheries Research, A Symposium Held in Bergen 19–22 June 1973, Margetts, A.R., Ed., *Rapports et Proces-Verbaux des Reunions*, 170, 52, 1977.
58. Kalikhman, I.L., Bondarenko, V.M., and Protaschuk, V.A., Investigation of multiple sound scattering in model concentrations, *Fisheries*, 4, 54, 1980 (in Russian).
59. Kalikhman, I.L., Bondarenko, V.M., and Protaschuk, V.A., Investigations of zones of detection of model concentrations by acoustic instruments, *Fisheries*, 6, 61, 1980 (in Russian).
60. Kalikhman, I.L., Bondarenko, V.M., and Protaschuk, V.A., Investigations of statistical characteristics of echo signals from model concentration of various density. *Fisheries*, 8, 47, 1980 (in Russian).
61. Shifrin, K.S., *Scattering of Light in a Turbid Medium*, NASA technical translation, NASA, Washington, DC, 212, 1968.
62. Bergmann, P.G., Yaspan, A., Gerjuoy, E., and Major, J.K., *Physics of Sound in the Sea*, Gordon and Breach, New York, 1968.
63. Ol'shevskii, V.V., *Statistical Methods in Sonar*, Consultants Bureau, New York, 1978 (translated from Russian).
64. Sukharevsky, Yu.M., Fluctuation pattern of sea reverberation, *Reports of the USSR Academy of Science*, 58(5), 787, 1947 (in Russian).
65. Yudanov, K.I., Gankov, O.E., and Shatoba, A.A., Experiments with artificial fish schools, *Fisheries*, 6, 25 and 7, 37, 1967 (in Russian).
66. Johnson, G.E. and Griffiths, W., Hydroacoustic surveys of zooplankton biomass and distribution in the Beaufort Sea in 1985 and 1986, in Developments in Fisheries Acoustics, A Symposium Held in Seattle, 22–26 June 1987, Karp, W.A., Ed., *Rapports et Proces-Verbaux des Reunions*, 189, 1990, 345.
67. Kasatkina, S.M., On commercial significance of krill aggregations, in Scientific Committee for the Conservation of Antarctic Marine Living Resources, Selected Scientific Papers, Hobart, Australia, WG-EMM-03/31, 9, 2003.
68. Yudanov, K.I. and Shatoba, O.E., Absorption of sound in fish concentrations, *Fisheries*, 4, 43, 1973 (in Russian).
69. Yudanov, K.I., Classification of echo-signals from fish concentrations, *Fisheries*, 6, 48, 1977 (in Russian).
70. Kuznetsov, P.I., Stratonovich, R.L., and Tikhonov, V.I., Eds., *Non-Linear Transformations of Stochastic Processes*, Wise, J. and Cooper, D.C., Trans., Eds., Pergamon Press, Oxford, 1965.
71. Marshall, S.J. and Hitschfeld, W., The interpretation of fluctuation echo for randomly distributed scatterers, *Canadian Journal of Physics*, 31, 962, 1953.
72. Smith, A.A., *Radio Frequency Principles and Application: The Generation, Propagation, and Reception of Signals and Noise*, Institute of Electrical and Electronics Engineers Press, New York, 219, 1998.
73. Tucker, D.G., *Underwater Observation Using Sonar*, Fishing News (Books), London, 144, 1966.

2 Scouting Characteristics of Acoustic Instruments

The differences in concentration reflectivity, the necessity of their detection, as well as qualitative and quantitative estimation are all reasons for placing special requirements on the characteristics of acoustic instruments. The first and foremost requirement is to achieve a maximal detection range and, in conjunction with this, a maximal detection zone. Another important requirement is sufficient resolving capacity of an instrument by range and angular coordinates. This is necessary in order to receive, on one hand, reliable data on spatial distribution of concentrations, and, on the other, a precise definition of the vertical borders of concentrations.

This chapter shows how the major characteristics of fish-finding instruments are determined and to what extent they satisfy the requirements. A rational choice of the major parameters of acoustic instruments is considered as well.

2.1 RANGE OF DETECTION OF COMMERCIAL ITEMS

The possibilities of detecting concentrations in some commercial fishing area depend, largely, on the detection range of the employed acoustic instruments. The detection range of an echo sounder should ensure the registration of fishery items down to the maximal depth of their habitation. In contrast to echo sounders, required ranges of sonar are determined not only by the demands of detection, but also by the necessity to aim the fishing gear reliably at commercial items. For this purpose, sonars with circular and wide sector views are used. Having great functional possibilities, these sonars are designed, first of all, to ensure aimed fisheries; their range does not usually exceed 1500–2000 m. Side scanning sonar are also used; their range can exceed 3000 m and more.

The approximate detection ranges of acoustic instruments required for ensuring an effective search are given in the Table 2.1. These data result from generalizing practical experience with consideration given to analysis of the peculiarities of the distribution of various items within different regions and the capabilities of fisheries vessels.

Estimating the detection range of an acoustic instrument is made with respect to a specific standard target. An individual target with a radius of equivalent sphere of $R_{eq} = 0.1$ m is considered as such standard for an echo sounder. This target corresponds, in a reflectivity, to a commercial fish of about 50 cm long. Orienting towards detection of single targets when vertical location is explained by the fact that echo sounders must ensure the search of not only dense concentrations, but also the registration of individual specimens. Regarding horizontal location, an individual target with a reflectivity of $R_{eq} = 2.0$ m is considered a standard item; a commercial

TABLE 2.1
Detection ranges for fish-finding equipment (FFE)

		Maximal Range (m)		
Purpose	**Operation Frequency (kHz)**	**Echo Sounders**	**Sonar**	**Area of Application**
FFE for small fisheries vessel (<150 tons, <200 horsepower)	150–200	30–50	—	Internal and shallow waters
FFE for small-tonnage vessels (>150 tons, >200 horsepower)	50–80	200–300	800–1000	Coastal areas of seas
	150–200	100–150	—	
FFE for middle-tonnage vessels (>800 tons, >700 horsepower)	20–30	500–600	1500–2000	Sea shelves
	100–150	200–250	—	
FFE for large-tonnage vessels (>2500 tons, >2500 horsepower)	20–30	1000–1500	3000–3500	Shelves, pelagic areas, underwater mountains
	100–150	300–350	—	
FFE for large-tonnage vessels (>5000 tons, >6000 horsepower)	15–20	1800–2500	3000–3500	Great depths
	100–150	500–700		

school, a cross section of which is much smaller than the detection zone of sonar, is implied. The point is that commercial schools are the major targets for a sonar search as well as for determining the aiming direction of fishing gears.

The detection range of a fish-finding instrument can be determined, in fact, from the main sonar equation[1]:

$$r^4 10^{0.2\alpha r} = \frac{P_a \gamma \sigma}{(4\pi)^2 I_{min}} \qquad (2.1)$$

where α is the coefficient of spatial attenuation of the sound energy in water, dB/m; γ is the coefficient of axis concentration of the transducer; P_a is the acoustic power of insonification, W; and I_{min} is the minimal intensity of echo signals, received by the transducer, W/m^2.

The energetic potential is used when estimating search possibilities of acoustic instruments, which is calculated from the following formula:*

$$\Pi = \frac{P_a \gamma}{(4\pi)^2 I_{min}} \tag{2.2}$$

The energetic potential gives an idea of the detection range of an instrument and allows coming to conclusions as to search capacities of a set of equipment as a whole. It estimates the real sensitivity of an instrument taking into account the conditions of its utilization. It is evident from Equation (2.1) and Equation (2.2) that the maximal detection range of the instrument can be calculated from the formula:

$$r^4 10^{0.2\alpha r} = \Pi\sigma \tag{2.3}$$

Calculation of the detection range is made taking into account the attenuation of the sound in water. It is convenient to transform formula (2.3) into the following form:

$$r_o/r = 10^{0.05\alpha r} \tag{2.4}$$

where r_o is the detection range of an instrument in the absence of attenuation.

Taking a logarithm of expression (2.4), we obtain:

$$\log(r_o/r) = 0.05\alpha r \tag{2.5}$$

It is easy solving this equation graphically. The left-hand side of the equation expressing the dependence of the relation r_o/r on the value α with various r_o, represents the group of the curves shown in Figure 2.1. The same figure shows the right-hand side of the equation as the group of straight lines corresponding to various values of α. The required value is found at the point of intersection of the given curve with the corresponding straight line.

The calculated detection ranges of equipment may differ slightly from the real ones, as rough estimates of the level of acoustic noises and sound attenuation are used. One can estimate even more roughly the theoretical capabilities of detecting surface or demersal concentrations, which are determined not only by the resolution of the equipment but also by the work efficiency of the scale expander of registration of concentrations, the device for breaking bottom signals, the transducer stabilizer, and so on.

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* The logarithmic expression of energetic potential is defined as a quality of an acoustic instrument.

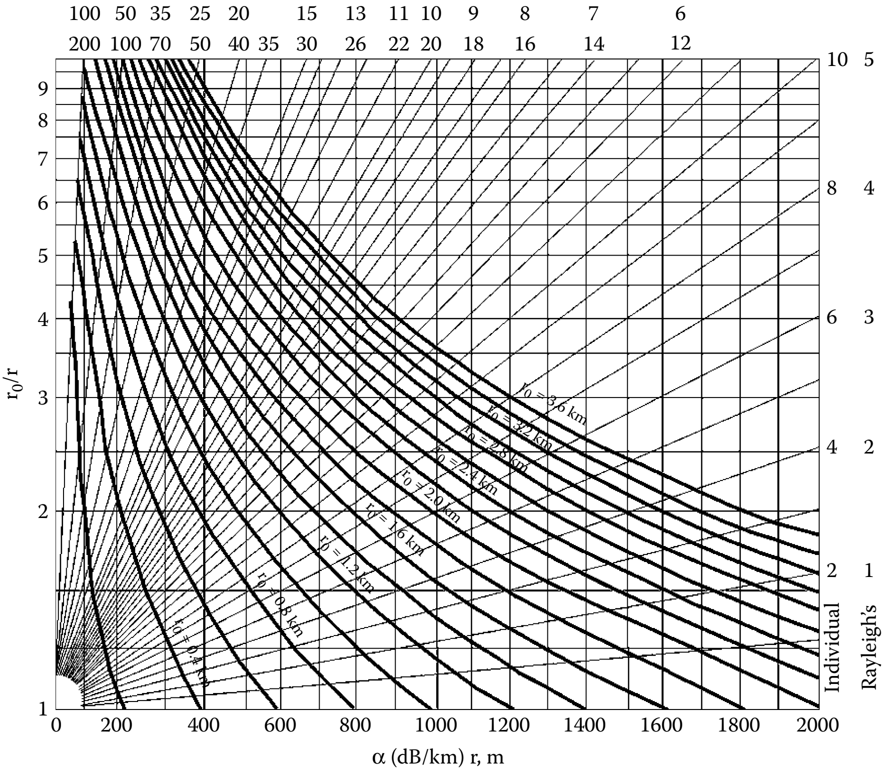

FIGURE 2.1 Dependence of the range of detection on the attenuation of sound in water.

It should also be taken into account that the scattering, attenuation, and acoustic noises in a water medium have a strongly fluctuating, stochastic character, while search and acoustic surveys are usually carried out with a high probability of item detection. As investigations show,[2] with a high probability of detecting item concentrations (0.90–0.95), the detection range of acoustic instruments should be nearly the same as that for reliable detection. At present, therefore, the deterministic approach is being applied when estimating the detection range. Average values of parameters given in formulas (2.1) and (2.3) are used; values of echo signals from commercial items should exceed the noise level.

Calculating the detection range of instruments by standard targets allows testing the possibilities of various echo sounders and sonar and comparing the search qualities of different equipment.* Calculated from formula 2.3, dependences of the range of detecting standard targets with R_{eq} = 0.1 m and R_{eq} = 2.0 m from a drifting vessel in calm weather, on the energetic potentials of an EK60 Scientific Sounder System operating at different frequencies, are given in Figure 2.2. Let us consider, for example, the range of detecting a standard target with R_{eq} = 0.1 m. With the

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* Regarding sonar, the geometric range is calculated ignoring vertical refraction of the sonic beam because of heterogeneities of the water medium.

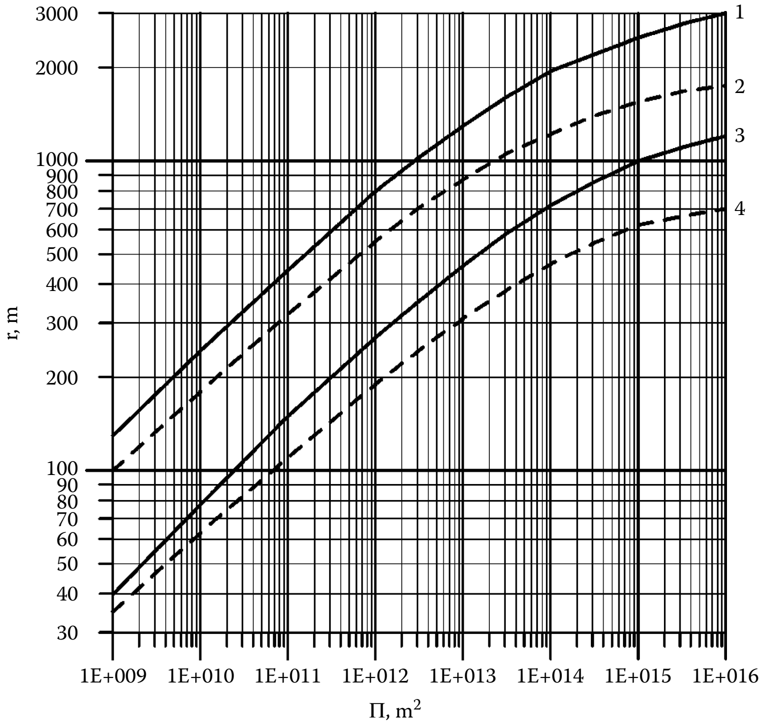

FIGURE 2.2 Dependence of the range of detection of standard targets on the energetic potential of an EK60 Scientific Sounder System operating at different frequencies: 1, f = 38 kHz, R_{eq} = 2.0 m; 2, f = 120 kHz, R_{eq} = 2.0 m; 3, f = 38 kHz, R_{eq} = 0.1 m; 4, f = 120 kHz, R_{eq} = 0.1 m.

energetic potential of the instrument at low frequency (38 kHz), $\Pi = 10^{15}$ m²; the graph shows that the detection range r = 1000 m. At high frequency (120 kHz), $\Pi = 10^{16}$ m²; the detection range r = 700 m.

The calculated detection ranges of various acoustic instruments show that the equipment in use by fisheries fleets satisfies the requirements of detection of commercial concentrations.

To clearly understand the real capabilities of detecting specific items, it is necessary to know their acoustic sections. In dispersed distributions of concentrations, when the instrument registers each specimen separately, it is necessary to know the acoustic section of individual items (σ) for determining the range from formula (2.3). As it was presented in Section 1.3, for dense concentrations, in which specimens keep close to each other and are registered by the instrument as a mass, the acoustic section of the concentration is determined by formula (1.21). Substituting expression (1.21) into formula (2.3), we obtain:

$$r^2\, 10^{0.2\alpha r} = \Pi\, \frac{c\tau}{2}\, m_v\, \Psi \tag{2.6}$$

In determining the required detection ranges of acoustic instruments, it is necessary to take into account the specific peculiarity of item distribution by depth. Larger items are usually distributed at greater depths and do not form as dense concentrations as smaller ones. Therefore, in estimating possibilities of detecting concentrations of larger fish at great depths, it is necessary to know the ranges of registration of dispersed concentrations or of individual specimens. Smaller items often form schools, keeping to comparatively shallow depths. It is useful to determine the limiting possibilities of detecting schools regarding sonar as, in this case, the energetic possibilities of echo sounders are usually not fully used.

In estimating real ranges, an additional (to the kilometrical) sound attenuation in the surface layer of the sea is required, which can be great in a horizontal direction. Air bubbles formed under the bottom of a ship by its motion because of the roughness of the sea play the major role in this additional attenuation. Measurements show that this additional attenuation depends largely on weather conditions, the speed of ship motion, and the operating frequency of the acoustic instrument.[3–5] By increasing the sea roughness and speed of ship motion, an especially great attenuation is observed at low frequencies.

Calculations from formulas (2.3) and (2.6) allow for estimating the possible range of an acoustic instrument for detecting fisheries items within a specific commercial region. Such estimation may be sufficiently precise regarding traditional fisheries region, in which the peculiarities of distribution, concentration densities, and their species and length composition are well known.

The previous discussion demonstrated that the energetic potential of acoustic instruments fully characterizes the maximal range of detecting the various items. The tests of fish-finding instruments for various purposes show that this equipment can ensure the detection of practically all species of commercial items down to the maximal depths of their habitation.* Deep-sea fishes are an exception.

The detection of deep-sea fishes (down to 2500 m and deeper) becomes possible when a transducer can be maneuvered sufficiently close to items of the search; i.e., by utilizing submerged towed transducers. Experimental testing proves the possibility of detecting commercial concentrations at depths of 2000 m when a transducer is towed at depths of 1000 m and deeper.

The detection of dispersed concentrations of krill and various small species of plankton has so far presented a serious problem. Control fishing and underwater observations showed that dispersed concentrations of plankton organisms could be observed in the upper layers as well as at considerable depths (200 m and deeper). However, such concentrations were poorly detected or not registered at all by acoustic instruments. The detection of plankton concentrations at considerable depths will eventually become possible as a result of using high-frequency acoustic instruments with a large energetic potential ($\Pi > 10^{16}$) and submerged transducer.

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* It is assumed that commercial concentrations are not masked by reflections from the sea surface, bottom, or sound-scattering layers. These cases of detecting concentrations will be considered in Chapter 4.

2.2 ZONE OF DETECTION OF COMMERCIAL ITEMS

If the potential of an acoustic instrument is to be fully exploited in the search for fish, it is important to have an accurate idea of the size of the zone encompassed by the instrument and to know its range in various directions. If we plot the distances at corresponding angles, using the transducer as the point of origin, we obtain the spatial characteristic of the range of an instrument in different directions. However, since it is laborious work to calculate and plot such spatial range zones of acoustic instruments, it is recommended to use the curves of intersection of these zones in certain directions; i.e., the so-called plane polar range characteristics.

Polar range characteristics are also referred to as detection zones of acoustic instruments or zones of detecting biological items. The polar range characteristic of an acoustic instrument is the geometric location of the points representing the position of the given target under the condition that the magnitude of the echo signal has the same minimum value required for its detection. The polar range characteristic is determined by the following factors: the directivity of a transducer, the sensitivity of an instrument, and the reflective properties of a recorded item. The range characteristics thus combine the properties of the acoustic instrument and those of the target and, hence, characterize better the fish-finding properties of the instrument.

Let us consider detection zones of fish-finding instruments regarding various commercial items. Specific peculiarities of sound scattering by individual marine animals and their concentrations (see Sections 1.2 and 1.3) serve for various methodological approaches in determining detection zones of acoustic instruments. Let us discuss the peculiarities of determining zones of detecting individual items and their concentrations.

The zone of detection of an individual item by an acoustic instrument can be ascertained analytically or experimentally. A method used in practice is as follows[6]: From the many traces of individual fish on an echogram for any depth, a series of recordings with apparent symmetrically dropping ends are selected. The length of such recordings determines the distance that the ship has traveled during the registration, corresponding to the longitudinal section of the zone. By making such measurements at various depths, one can estimate the detection zone of the echo sounder for various depths and create a polar range diagram.

Another widely used method of determining the section of the zone is by the average number of echo signals from one fish.[6] As a rule, this is found with the echo counter, the sensitivity of which should be the same as that of the echo recorder. Dividing the number of echo signals that are recorded during a certain period by the number of fish counted in the echogram gives the average number of echo signals from one fish n_1. The longitudinal section of the zone is calculated from the following formula:

$$D_{long} = \frac{\sqrt{k_f}\, v_{vess}\, n_1}{f_{imp}} \tag{2.7}$$

where v_{vess} is the speed of the vessel movement, f_{imp} is the rate of transmissions (pings), and k_f is the coefficient of form of detection zone.

For round transducers, $k_f = 4/\pi$; for rectangular ones, k_f is approximately equal to $4/\pi$.

The transversal section of the detection zone determining the width of the surveyed area is determined from the following formula[6]:

$$D_{trans} = D_{long}\ a/b \tag{2.8}$$

where a and b are effective dimensions of the transducer in the longitudinal and transversal planes, respectively. Detection zones for other depths are found similarly.

The zone of detection of an object by a fish-finding instrument can be obtained analytically.[6] In this case, the range of detecting a fish situated at the angle θ to the acoustic axis is calculated from the equation:

$$r_\theta = r_{max} \sqrt[4]{G(\theta)}\ 10^{0.05\alpha(r_{max} - r_\theta)} \tag{2.9}$$

where r_{max} is the detection range in axis direction and G(θ) is the transducer directivity function by acoustic pressure when transmitting or receiving in a respective plane.

The detection zone depends on the time-varied gain (TVG). To remove the effect of attenuation and the spreading of the wave front with depth, when registering individual targets, the TVG should increase the gain according to the quasi-square law[6]

$$\mu = \mu_o (r/r_o)^2 10^{0.1\alpha(r - r_o)} \tag{2.10}$$

where r_o is the range of TVG action and μ_o is the gain beyond the range of the TVG action.

A different TVG law is necessary for excluding the dependence of integrator readings on the depth of locating fish concentrations. In this case, the TVG should increase the gain according to the quasi-linear law:

$$\mu = \mu_o (r/r_o) 10^{0.1\alpha(r - r_o)} \tag{2.11}$$

According to the chosen TVG law, the directivity factor is determined[6]

$$G_{TVG}{}^4 = \frac{r_o{}^4}{\Pi\sigma} \tag{2.12}$$

$$G_{TVG}{}^4 = \frac{r_o{}^2 r^2}{\Pi\sigma} \tag{2.13}$$

Knowing the detection range in the axis direction, which is determined from formula (2.3), and the directivity function of a transducer, it is possible to calculate from formula (2.9) the detection range in various directions. Let us calculate the detection zone with regard to an EK60 Scientific Sounder System and a standard target with $R_{eq} = 0.1$ m (Figure 2.3). As the figure demonstrates, with the TVG by the quasi-square law, the detection zone takes a conic shape and its side lobes are completely removed. Consequently, the correct choice of the TVG makes it possible, even with a wide transducer directivity, to obtain a fairly narrow detection zone. A narrow detection zone is necessary for calibrating the instrument, for fish scouting near the bottom, and for the analysis of distortions in recording of fish concentrations and schools.

The detection zones of individual objects are also affected by the speed of vessel movement.[6] Search experience shows that, when detecting fish against a background of disturbances, the motion of the vessel causes a narrowing of the detection zone, a decrease in the maximal range of detection, and the appearance of "dead zones" at short distances.

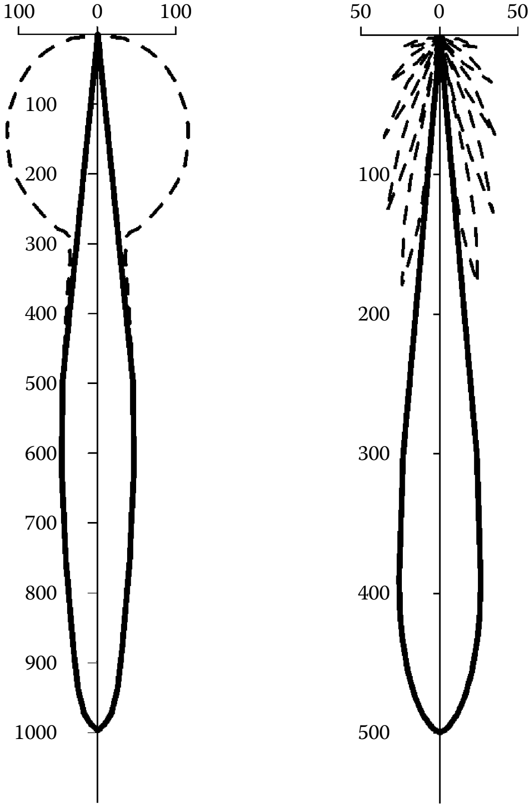

FIGURE 2.3 Zones of detecting an individual fish ($\sigma_{fish} = 314$ cm^2) by an EK60 Scientific Sounder System operating with the TVG by the quasi-square law at 38 kHz ($\Pi = 10^{15}$ m^2, $r_o = 500$ m, left) and 120 kHz ($\Pi = 10^{16}$ m^2, $r_o = 400$ m, right). The dashed lines show the detection zones without the TVG.

The zone of detection of an item concentration by an acoustic instrument is a space area confined by concentration sections that are the most remote from the acoustic axis and which account for threshold echo signals.[6] A threshold signal is the summary reflection from individual items located in the periphery of an impulse volume (Figure 2.4). The range of detecting the periphery section of a concentration is determined from the equation:

$$r_{per}^{4} = \Pi\sigma_{per}10^{-0.2\alpha r_{per}} \tag{2.14}$$

where σ_{per} is the average value of the acoustic section of commercial items located in the periphery section of an impulse volume.

According to relations (1.19) and (1.20)

$$\sigma_{per} = \frac{c\tau}{2}\, r_{per}^{2} m_v \Psi(\theta_{eff}, \theta_{max}) \tag{2.15}$$

where θ_{eff} is the effective width of the acoustic beam of the instrument and θ_{max} is the maximal value of the width of the sound beam.

Substituting expression (2.15) into (2.14), we obtain

$$r_{per}^{2} = \Pi\frac{c\tau}{2}\, m_v \Psi(\theta_{eff}, \theta_{max}) 10^{-0.2\alpha r_{per}} \tag{2.16}$$

With application of the TVG by the quasi-linear law (2.11), the integral directivity factor is constant and is determined from the following formula:[6]

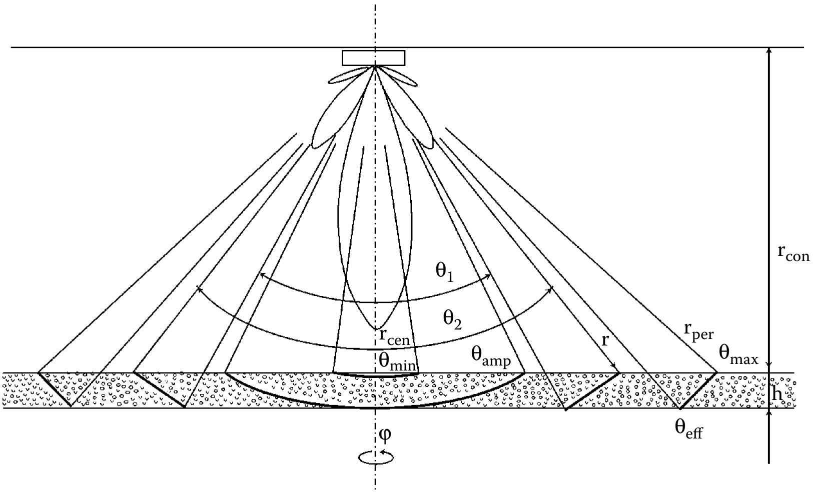

FIGURE 2.4 Scheme of the mutual position of a transducer and a fish concentration.

$$\Psi(\theta_{eff},\theta_{max}) = \frac{r_o^{\,2}}{\Pi\left(c\tau/2\right)m_v} \tag{2.17}$$

Equation (2.16) and Equation (2.17) make it possible to calculate and plot the zone of detection of a fish concentration registered by an acoustic instrument. Figure 2.5 shows the results of calculating the detection zones with an EK60 Scientific Sounder System operating at different frequencies. As seen in the figure, with the TVG by the quasi-linear law, the detection zone takes a conic shape and its side lobes are completely removed. Exclusion of the side lobes of the directivity characteristic allows a substantial decrease of distortions in recording commercial concentrations, especially at shallow depths, as well as of the masking effect of sound scattering layers (SSL) located in surface horizons. Calculations show that as density increases, the range of detecting the concentration increases as well and the detection zone gets larger. The decrease of the thickness of a concentration leads to a decreased detection zone.

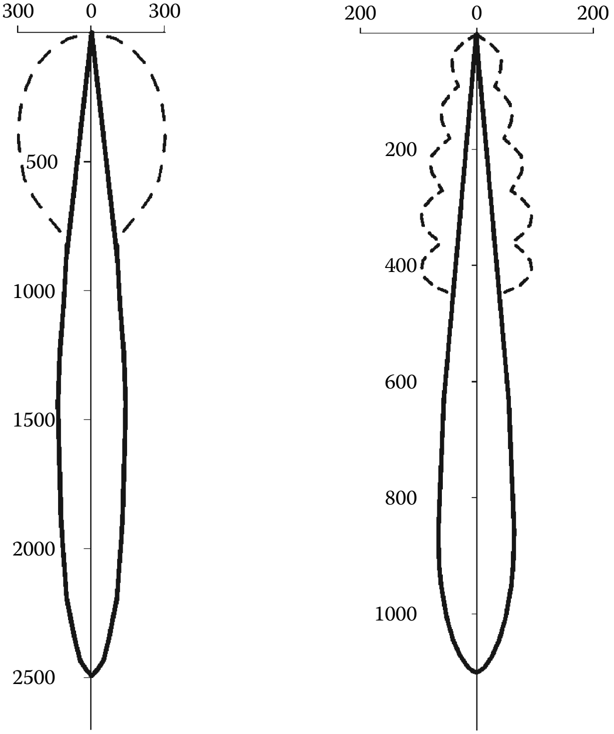

FIGURE 2.5 Zones of detecting a fish concentration (σ = 10 cm^2, ρ_v = 0.1 sp/m^3, h = 50 m) by an EK60 Scientific Sounder System operating with the TVG by the quasi-linear law at 38 kHz (Π = 10^{15} m^2, r_o = 800 m, left) and 120 kHz (Π = 10^{16} m^2, r_o = 600 m, right). The dashed lines show the detection zones without the TVG.

Special attention should be paid to the influence of the acoustic characteristics of fish on detection zones.[6] Function $\Psi(\theta_1,\theta_2)$ above was taken as the integral function of the directivity of the transducer, which does not take into account differences in the reflectivity of fish insonified by the acoustic wave from different directions $G_{fish}^2(\theta)$. Fish in the peripheral sections of the concentration can be insonified from any direction within the solid angle of 2π steradians. Numerous measurements of fish scattering show that the nonuniformity of the backscattering from fish with such a wide range of insonification direction can be fairly high, especially at high frequencies. Therefore, when calculating zones of detection of concentrations with acoustic instruments, it is necessary to take into account the directivity of the backscattering from fish.

Figure 2.6 shows the zones of detection of the fish concentration calculated by the usual method and with consideration of the influence of the directivity of backscattering. The figure presents a considerable effect if the acoustic instrument is used for detecting surface concentrations of fish without TVG. In the above example, the value of the side lobes of the detection zone calculated by the usual method is overrated more than twofold. With increasing depth of the concentration, the influence of the directivity of backscattering decreases.

Figure 2.4 shows that the penetration of waves into the concentration from the central part of the packet is gradual; therefore, the beginning of registration does not correspond to the upper border of the layer. Concentration areas adjacent to the acoustic axis, which give echo signals below the threshold level of registration, form a dead zone in detecting the upper edge of the layer.[6] The range of detection of the central section of fish concentration is determined from the equation

$$r_{cen}^2 = \Pi \frac{c\tau}{2} m_v \Psi(0,\theta_{min}) 10^{-0.2\alpha r_{cen}} \tag{2.18}$$

where θ_{min} is the minimal value of directivity width (Figure 2.4).

With application of the TVG by the quasi-linear law (2.11), the integral directivity factor is constant and is determined from the following formula:[6]

$$\Psi(0,\theta_{min}) = \frac{r_o^2}{\Pi\left(c\tau/2\right)m_v} \tag{2.19}$$

If the concentration is located at various depths, the values of “dead zones” are considerably different. Dependence of θ_{min} on the distance at detecting the upper edge of the layer shown in the polar coordinate system is the angular diagram of the dead zone at detecting the upper border of the concentration.

Figure 2.7 shows the angular diagrams of dead zones when the concentration is detected by an EK60 Scientific Sounder System. When the TVG is used, the integral directivity factor corresponding to the moment of detecting the upper border of the layer does not depend on the depth of the concentration. The angular diagrams

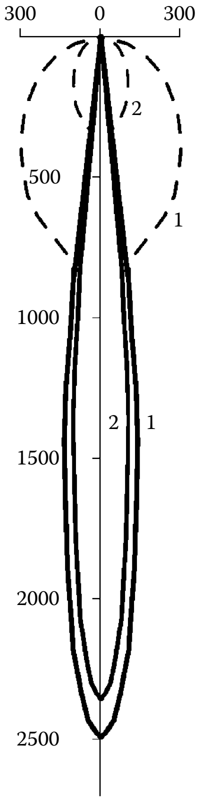

FIGURE 2.6 Zones of detecting a fish concentration (σ = 10 cm^2, ρ_v = 0.1 sp/m^3, h = 50 m) by an EK60 Scientific Sounder System operating with the TVG by the quasi-linear law at 38 kHz (Π = 10^{15} m^2, r$_o$ = 800 m): 1, calculated by the usual method; 2, calculated with consideration for effect of spatial acoustic backscattering by fish (herring 22.5 cm long). The dashed lines show the detection zones without the TVG.

of dead zones in this case are constant at any depths. Thus, the use of the TVG leads to a larger dead zone in detecting the upper border of the concentration.

The above methods allow for drawing the zones of detecting commercial items, determining the effective width of an ultrasound beam of a fish-finding instrument regarding registration of individual items and concentrations. As will be shown in further sections of the book, the knowledge of the effective width is necessary for solving various problems connected to the search of commercial concentrations and to biomass estimation. The precision of the elaborated methods for the zone estimation was verified experimentally by standard targets and by artificial model concentrations.[7] The results confirmed the reliability of the methods; the deviations of experimental data from the results of calculations from formulas (2.9) and (2.16) do not exceed 20%.

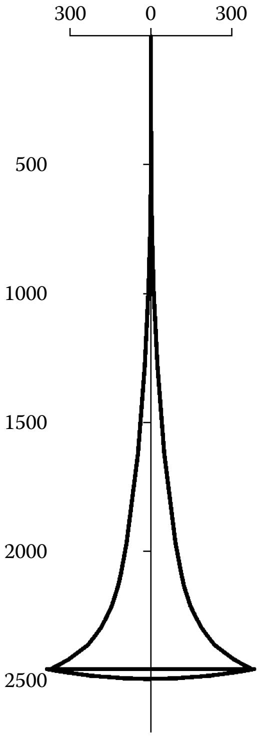

FIGURE 2.7 Angular diagrams of "dead zones" in detecting the upper border of a fish concentration (σ = 10 cm^2, ρ_v = 0.1 sp/m^3, h = 50 m) by an EK60 Scientific Sounder System operating with the TVG by the quasi-linear law at 38 kHz ($\Pi = 10^{15}$ m^2, r_o = 800 m).

2.3 RESOLVING CAPACITY OF ACOUSTIC INSTRUMENTS

The resolving capacity of fish-finding instruments is important in the search and quantitative estimation of commercial items. It plays the major role in the efficiency of detection and interpretation of concentrations. The resolving capacity is differentiated as follows: by range (distance or depth), by angle (azimuth or direction), and by volume.

Resolution by range is determined by the minimal distance between two items, with which they can be registered separately, one from the other, on the indicator. It is assumed that the items are situated in the radial direction relative to the transducer; i.e., they have the same angular coordinates. In this case, the resolution in registering schools or concentrations is equal to[8]

$$\delta_r = \left(\tau + \frac{1}{\Delta f}\right)\frac{c}{2} + \frac{d}{v_1}\frac{c}{2} + r\left(\sec\frac{\theta_{eff}}{2} - 1\right) + H \tag{2.20}$$

where Δf is the bandwidth of the amplifier, d is the dimension of a point mark on the indicator (clearness of registration), v_1 is the speed of linear scanning of the indicator by the range, and H is the extension of the concentration in the direction of location.

In calculating the resolving capacity in regard to the registration of individual fish, the latter two items in formula (2.20) can be excluded.

Let us determine the resolution of the echo sounder using formula (2.20); let us assume that the impulse duration $\tau = 1.0\,\text{ms}$, the amplifier bandwidth $\Delta f = 1.2$ kHz, the speed of scanning in operating on the 200-meter display range $v_1 = 0.7$ m/s, the dimension of a point mark d = 0.5 mm. Substituting these values into the formula for calculating the resolution, we obtain:

$$\delta_r = \left(1 + \frac{1}{1.2}\right)\frac{1500 \times 10^{-3}}{2} + \frac{0.5}{0.7}\frac{1500 \times 10^{-3}}{2} = 1.4 + 0.6 = 2.0 \text{ m}$$

In operating on 300-meter range ($v_1 = 0.45$ m/s), the resolution of the instrument will be lower and equal to $\delta_r = 2.3$ m.

The calculations from formula (2.20) show that, regarding the majority of fish-finding echo sounders, the resolution by depth in registering individual items differs only slightly from the values of δ_r received.

In registering schools and concentrations, the resolving capacity is worse. Thus, the resolution of the echo sounder when detecting a fish concentration with a thickness of H = 10 m, situated at a depth of r = 300 m, with $\theta_{eff} = 11^\circ$, is equal to

$$\delta_r = 2 + 300(\sec 5.5^\circ - 1) + 10 = 18 \text{ m}$$

Calculated value of the resolving capacity shows that the echo sounder will register fish concentrations together with recording of the ground even if fish keep at a considerable distance from it. With such resolution of the echo sounder, a wrong picture of the distribution of demersal concentrations is created, which may, in turn, adversely affect the results of search and fishery of items.

Formula (2.20) indicates that increasing the resolving capacity can be achieved by narrowing the acoustic beam of the instrument, decreasing the duration of transmissions, and increasing the speed of scanning and clearness of registration. Indeed, high-frequency echo sounders with impulse duration of $\tau = 0.1$–0.2 ms have a rather high resolution by depth, concerning individual items as well as concentrations. In addition, using electronic color indicators and devices for breaking bottom signals give reliable results.

Sonar has a much worse resolving capacity than echo sounders as it has a larger duration of transmissions and lower speed of scanning of indicator. Thus, in using sonar on the 1200-meter range ($v_1 = 0.1$ m/s and $\tau = 10\,\text{ms}$), the resolving capacity by range in registering individual items is equal to 15 m. In registering schools by sonar, the conditions of their resolution are even worse.

Two objects may be recorded separately even if the distance between them is smaller than the range of instrument resolution, or even if they are at the same echo distance but at different sides of the insonified zone; i.e., beyond the effective angle of the instrument.

Regarding sonar with a circular or sector view, the resolving capacity by azimuth is determined by the minimal angle, which is required to register two equally remote items on the screen of an electronic indicator. With electronic scanning, this angle is equal to[8]

$$\delta_\theta = \theta_{eff} + \Delta\theta \tag{2.21}$$

where $\Delta\theta = d/R$ is the angular resolution of an indicator screen and R is the radius of the screen of an electronic tube.

Taking into account that in fish location, one often has to deal with objects of large angular extent (schools, shoals), it is more convenient to express the resolving capacity by angle in units of length rather than in degrees. In this case, the tangential resolution of an acoustic instrument is considered. The resolving capacity of sonar in registering large objects can be found from the following expression[8]:

$$\delta_L = r\delta_\theta + L = r\theta_{eff} + L \tag{2.22}$$

where L is the linear dimension of an object. For example, with r = 500 m, L = 50 m, and $\theta_{eff} = 5^\circ$, the resolution of sonar by angle $\delta_\theta = 5^\circ = 0.09$ rad and, consequently, $\theta_L = 500 \times 0.09 + 50 = 95$ m.

Let us consider now the resolution of an echo sounder by angle. The tangential resolution of an echo sounder can be expressed as[8]:

$$\delta_L = 2r \operatorname{tg} \frac{\theta_{eff}}{2} + d \frac{v_{vess}}{v_2} + L \tag{2.23}$$

where v_{vess} is the speed of vessel movement and v_2 is the speed of the interline scanning of the indicator.

When registering individual fish, the last item in formula (2.23) can be excluded. Let us determine the typical value of the tangential resolution of an echo sounder from this formula. For example, with $v_{vess} = 92.6$ m/min (3.0 knots), $v_2 = 8.5$ mm/min (the range of 200 m), d = 0.3 mm, r = 200 m, and $\delta_{eff} = 10^\circ$, the tangential resolution $\delta_L = 41.7$ m.

The resolving capacity of an echo sounder by angle strongly depends on the speed of vessel movement v_{vess} and the speed of scanning v_2. With a slow scanning speed, echo signals are registered near each other and clearer tracks overlap weaker ones. This leads to a lowering of the clearness of a recording, to increasing d. The increase of the speed of vessel movement results in an analogous phenomenon. Thus, with a speed of vessel movement of 10 knots ($v_{vess} = 308.7$ m/min.), d = 1.0 mm, the tangential resolution $\delta_L = 74.7$ m.

The majority of fish-finding echo sounders being used by the fisheries fleet have a similar value of the resolving capacity. The fact that individual fish are registered all together even when they are located at a considerable distance from each other is explained by this circumstance. The same circumstance explains the fact that aggregations of low density are recorded on a printer tape as monolithic concentrations.

The tangential resolving capacity can be improved, first, by using the narrow directivity diagram of a transducer.

The resolving volume is a generalized measure of the resolving capacity. It characterizes the area of the space within the limits of which objects are registered all together, while outside, separately. The dimensions of the resolving volume depend on the directivity diagram of a transducer and the duration of transmissions. The value of resolving or impulse volume is equal to[6]

$$V_{imp} = \frac{\pi}{8}\, c\tau\theta_{eff}{}^{2}r^{2} \tag{2.24}$$

As seen from relation (2.24), the value of resolving volume greatly changes with depth. This means that, with the same density of a dispersed concentration, fish situated at a shallower depth may be registered separately, and at a greater one, all together. The limiting concentration density, at which a separate registration is possible, is

$$\rho_{lim} < 1/V_{imp} = 8(\pi c\tau\theta_{eff}{}^{2}r^{2})^{-1} \tag{2.25}$$

Using formula (2.25) and polar characteristics, presented in Figure 2.3, we calculated the values of the limiting concentration density concerning various depths and an EK60 Scientific Sounder System operating at various frequencies (Figure 2.8). The graph demonstrates that at a low frequency, even with a shallow depth, the limiting concentration density is not high (on the order of 0.01 sp/m^3). At a high frequency, this density can reach 0.05 sp/m^3 and more.

Thus, the resolving capacity of a low frequency instrument ensures a separate registration of items only in locating highly dispersed concentrations. Only narrow-beam, high-frequency instruments allow for registering individual items in dense enough concentrations. As will be shown in Chapters 5 and 6, the possibility of separate registration of items is very important in species, length, and quantitative interpretation of commercial concentrations.

2.4 RATIONAL CHOICE OF PARAMETERS OF ACOUSTIC INSTRUMENTS

As demonstrated by the aforementioned brief analysis of the main scouting characteristics, requirements for the parameters of acoustic equipment must take into account the peculiarities of distribution of fish, their reflectivity, and the operating conditions of the equipment. As various fish species possess different reflectivity, typical depth, and character of distribution, requirements for the parameters of acoustic equipment may vary strongly even within a comparatively small commercial

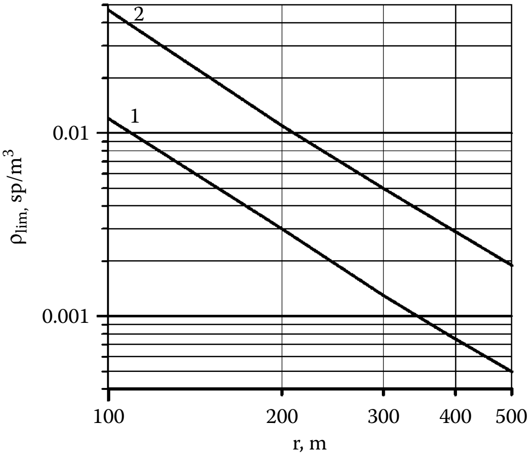

FIGURE 2.8 Dependence of the limiting density on the distance to a fish concentration for an EK60 Scientific Sounder System operating at various frequencies: 1, 38 kHz ($c\tau = 1.5$ m, $\theta_{\text{eff}} = 7°$); 2, 120 kHz ($c\tau = 0.375$ m, $\theta_{\text{eff}} = 7°$).

region. The requirements for fish-finding instruments may be even greater regarding various regions.

The requirements for instruments with regard to their detection range are especially varied. The development of oceanic fisheries shows that commercial concentrations are recorded not only over shelves but also in deep water regions of the World Ocean. Therefore, depending on the region of work and the item of fisheries, the requirements for detection range can vary strongly. The achievement of the required range is connected to the correct choice of the operation frequency and acoustic power of the instrument. Optimal sensitivity of the equipment receiver also plays a rather important role.

Because of different fish distribution patterns within the water bodies, there are various requirements for instruments regarding their resolving capacity. Thus, the reconnaissance of demersal concentrations must be carried out by instruments with possibly higher resolution; i.e., a narrow ultrasonic beam and short transmissions are required. In contrast, when searching pelagic concentrations, especially when fish keep separated, for detecting fish readings against a background of disturbances, it is practical to use echo sounders with a rather wide ultrasonic beam.

Since distribution of the majority of commercial items during the day is subject to considerable change (pelagic concentrations may transform to demersal ones and vice versa; concentration density can change), it is necessary, for effective search of commercial concentrations, to utilize instruments with different operating frequencies, impulse durations, directivity characteristics, and so on. Let us discuss the rational choice of these parameters in detail.

CHARACTERISTICS OF TRANSDUCER DIRECTIVITY

Reliable detection of individual fish is the main requirement in choosing the characteristic of directivity of an echo sounder transducer. Accomplishing this requirement depends, largely, on conditions of tossing of vessels. The major parameters of tossing of middle- and large-tonnage vessels at various sea states are given in Table 2.2. We reached the cited values by averaging a large number of measurements with different directions of vessel motion relative to a wave and at a speed of 5–8 knots.

The table illustrates that the rolling and pitching of a vessel may cause considerable deviations of an ultrasonic beam of an echo sounder. Thus, with a wave height of 6–12 feet, when the angular speed of the list of a middle-tonnage vessel ω_l = 6.5°/s, the angular deviation of the beam for an interval between transmissions with the frequency of repetition of transmissions f_{imp} = 37.5 imp/min is equal to $\varphi_l = 60\omega_l/f_{imp} = 60 \times 6.5/37.5 = 10.4°$.

In order to ensure the regular registration of echo signals from fish in a rough sea, the following values are recommended for the width of the transducer directivity characteristic in the longitudinal (θ_{long}) and transversal (θ_{trans}) planes:

$$\theta_{long} = 2\varphi_{trim};\ \theta_{trans} = 2\varphi_{list} \qquad (2.26)$$

where φ_{trim} and φ_{list} are the angles of the trim difference and list of the vessel, accordingly.

As already mentioned in Section 2.1, in bad weather conditions, the search capabilities of echo sounders are restricted because of sound attenuation in the aerated surface water layer. In addition, in a rough sea, strong aeration causes a decrease in acoustic resistance of the water and transducer discordance with the medium, which, in turn, leads to abrupt lowering of efficiency of acoustic equipment.

TABLE 2.2
Parameters of tossing of various kinds of vessels

	Middle-Tonnage Vessels			**Large-Tonnage Vessels**		
	Wave Height (feet)					
Parameters of Tossing	**3.5–7.5**	**6–12**	**8–20**	**3.5–7.5**	**6–12**	**8–20**
List						
Angle, °	9.0	11.5	14.0	6.5	8.5	11.0
Period, s	7.0	7.0	6.5	12.0	11.5	11.5
Angular speed, °/s	5.0	6.5	8.5	2.0	3.0	4.0
Trim difference						
Angle, °	3.5	4.0	4.0	3.0	3.5	4.0
Period, s	4.0	4.0	3.5	6.0	5.5	5.5
Angular speed, °/s	3.5	4.0	4.5	2.0	2.5	3.0

Therefore, the search of commercial items is possible only up to a wave height of 6–12 feet regarding the middle-tonnage vessels and 8–20 feet in respect to large-tonnage ones.* Taking into account the aforementioned limitation by tossing and using the data from Table 2.2, we obtain from conditions (2.26) the following values of the width of the directivity characteristics of a transducer, mounted into the vessel bottom: $\theta_{long} = 7–8°$, $\theta_{trans} = 15–20°$.

With the final choice of the transducer directivity characteristic of fish-finding echo sounders, the conditions of registering individual items and limitations connected to the distortions in recording of concentrations should be taken into account.

Taking into consideration that, in order to detect individual fish against a background of impulse disturbances, it is necessary to receive from this fish no less than three echo signals, the width of the transducer directivity in the longitudinal plane θ_{long} should be equal to[8]

$$\theta_{long} = \frac{3v_{vess}}{rf_{imp}} \tag{2.27}$$

Calculations from formula (2.27) show that the angle $\theta_{long} = 8°$ is sufficient to detect individual fish at a wide range of depths. With such a value of θ_{long}, the detection capabilities will not be hampered as the zone of the view depends only upon the directivity angle in the transversal plane θ_{trans}.

The choice of the width of the transducer directivity characteristic of fish-finding echo sounders in the transversal plane θ_{trans} is determined by the required zone of the search and by distortions in registration, which grow rapidly with increasing angle and depth. Elementary calculations (see Section 4.2) show that an angle $\theta = 15–20°$ is sufficient from the point of view of the mentioned conditions. Thus, it is possible to consider a width of the directivity characteristic of $8 \times 20°$ as optimal for a large range of depths.

However, the suggested directivity characteristic cannot be universal for all cases of search. In particular, it does not guarantee a sufficiently wide detection zone when searching for commercial items at shallow depths, and at greater depths it leads to distortions in recordings. For this reason, small-range echo sounders (down to 50 m) should have, besides the mentioned major characteristic, an additional wider one ($\theta_{trans} = 25–30°$); large-range echo sounders (800–1000 m), also a narrow characteristic (θ_{trans} less than 10°).

In super-range echo sounders (more than 1000 m), it is necessary to apply very narrow-beam transducers for which stabilization is required. In a stabilized transducer, the directivity width in the longitudinal plane is determined by condition (2.27) only. Therefore, in super-range echo sounders, the directivity angle can be very small (3–5°).

To ensure a sufficiently wide zone of search in deepwater echo sounders, it is practical to apply electronic scanning of the narrow beam in a transversal plane of the vessel. Using a narrow ultrasonic beam in such echo sounders can be especially reliable because it reduces the masking of readings of deepwater demersal fish.

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* In order to ensure the search of commercial items under bad weather conditions, it is expedient to use a towed transducer, immersing it under the aerated water layer.

OPERATION FREQUENCY AND ACOUSTIC POWER

In choosing an operation frequency for fish-finding instruments, one has often to deal with contradictory demands. A rational frequency can be a compromise between lower frequencies, spreading with smaller losses, and higher ones, expedient from the point of view of directivity and noise level. Therefore, in regard to any specific conditions of search, there is always a certain optimal operation frequency.

If, when choosing the operation frequency, it is assumed that the sound attenuation and the threshold intensity of echo signals depend on the frequency alone, then in regard to specific values of the width of the transducer directivity characteristic, the calculation of the optimal frequency f_{opt} and acoustic power P_a can be made from the following formulas[9]:

$$f_{opt} = \frac{18.65}{r^{2/3}} \tag{2.28}$$

where f_{opt} is the frequency in kHz and r is the range in km;

$$P_a = \frac{32\pi^2 K_\delta{}^2 p_n{}^2 r^4}{B\gamma^2 \sigma T \rho c} \tag{2.29}$$

$$B = f^2 10^{-0.0072 f^{3/2} r} \tag{2.30}$$

where K_δ is the coefficient of reliability of detection; p_n is the acoustic pressure of disturbances, reduced to standard conditions ($f = 1.0$ kHz, $\Delta f = 1.0$ Hz, $\gamma = 1.0$); γ is the coefficient of axis concentration of a transducer; T is the time of averaging of a signal, corresponding to the duration of a transmission; and ρc is the acoustic resistance of water.

Using the cited formulas, let us calculate the optimal operation frequencies and acoustic power required for fish-finding instruments with detection ranges of 600 and 1200 m. From formula (2.18) we find that for a detection range of the instrument of 600 m, its optimal operation frequency should be equal to 26.3 kHz; for 1200 m, 16.5 kHz. In calculating acoustic power regarding the optimal transducer directivity characteristic ($\theta_{long} = 8°$, $\theta_{trans} = 20°$), let us use the following typical parameters[9]: $\gamma = 170$; $K_\delta = 1.1$; $T = 1.0$ ms; $\sigma = 314$ cm^2 ($R_{eq} = 0.1$ m). Average values of disturbance level in large-tonnage fisheries vessels at a speed of 3.0 knots and with a wave height of 3.5–7.5 feet, $p_n = 0.03$ Pa; at 8.0 knots and with the same sea state, $p_n = 0.1$ Pa; at 12 knots, $p_n = 0.3$ Pa.

Formulas (2.29) and (2.30) demonstrate that, in order to ensure the detection range of 600 m at the optimal operation frequency with a level of disturbances 0.1 Pa, acoustic power $P_a = 2.0$ kW is required. A range of 1200 m at the optimal operation frequency with the same level of disturbances can be achieved with P_a = 80 kW. The results of calculations at different frequencies show that the value P_a is slightly dependent on the frequency. Only a significant deviation from the optimal frequency requires a substantial increase in the acoustic power.

Since achieving high acoustic power encounters significant physical difficulties and is limited by the conditions of cavitation, the maximal acoustic power of a fish-finding instrument usually does not exceed 10 kW.

The graph in Figure 2.9 illustrates possible ranges of fish detection with an instrument operation frequency of 16.5 kHz under various search conditions. For example, the graph shows that with P_a = 10 kW, the detection of fish at a depth of 1200 m can be ensured only when operating at lowered speeds of vessel motion, in good weather. At a speed of 8.0 knots and p_n = 0.1 Pa, the instrument detection range is equal to 800 m; at 12 knots, 500 m. In rough weather, when the level of disturbances increases abruptly, the detection range decreases even more.

Some increase in detection range of fish-finding instruments can be achieved by increasing the coefficient of axis concentration with a narrowing of the directivity characteristic of a transducer. Narrowing the directivity is connected to increasing the size of a transducer and to applying systems of stabilizing the beam. Regarding the specific dimensions of a transducer, the coefficient of concentration depends on frequency. The optimal frequency and acoustic power can be calculated from the following formulas[10]:

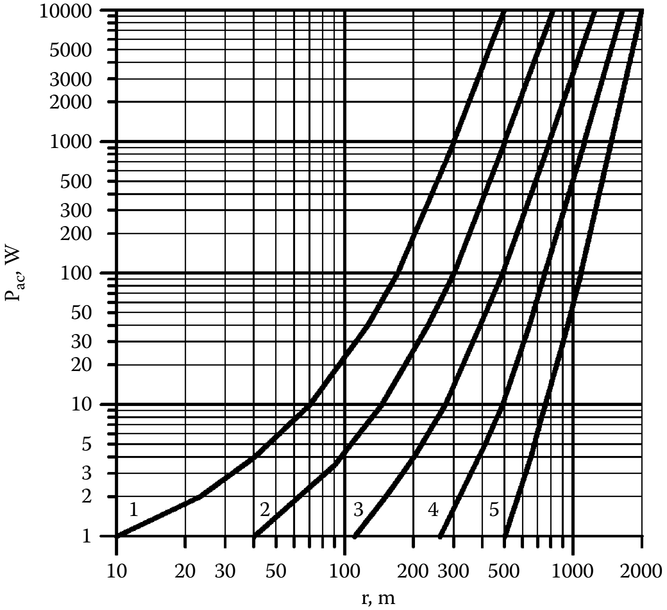


FIGURE 2.9 Dependence of the acoustic power on the detection range under various search conditions (1, f = 16.5 kHz, p_n = 0.3 Pa; 2, f = 16.5 kHz, p_n = 0.1 Pa; 3, f = 16.5 kHz, p_n = 0.03 Pa; 4, f = 30.0 kHz, p_n = 0.3 Pa; 5, f = 30.0 kHz, p_n = 0.1 Pa).

$$f_{opt} = \frac{39}{r^{2/3}} \tag{2.31}$$

$$P_a = \frac{2K_\delta{}^2 c^4 p_n{}^2 r^4}{BS^2 \sigma T \rho c} \tag{2.32}$$

$$B = f^2 10^{12} 10^{-0.0072 f^{3/2} r} \tag{2.33}$$

where S is the area of the active surface of a transducer.

Formula (2.31) shows that in order to detect fish at a distance of 1500 m, the optimal frequency of a narrow-beam fish-finding instrument should be 30 kHz. In this case, as follows from formulas (2.32) and (2.33), with the transversal size of a transducer equal to 1.0 m, $\gamma = 5020$, and the level of disturbances $p_n = 0.1$ P_a, an acoustic power of 1.1 kW is required; with $p_n = 0.3$, $P_a = 9.6$ kW. Figure 2.9 presents the calculated powers for other ranges of search. As the graph shows, using a narrow-beam transducer ensures reliable search of fish with $P_a = 10$ kW down to the depths of 1500 m.

It should, however, be noted that formulas (2.31)–(2.33) fit only for approximate calculations; they need an additional, more precise definition as dependences of the attenuation and the level of disturbances on the frequency require specification in regard to different conditions of the search.

In designing fish-finding instruments with a small detection range, as well as in detecting small marine organisms (krill, plankton), operation frequencies and acoustic powers have to be determined approximately. As previously mentioned in Section 1.5, for vertical location at shallow depths, when the absorption of sound at low ultrasonic frequencies in the upper water layer, saturated by air bubbles and other heterogeneities, make up the main part of the total attenuation, using echo sounders of high frequencies on the order of 100 kHz and more is most effective. The significant efficiency of high-frequency echo sounders is explained by their sharp directivity and by their lower level of reception of various noises. Practice shows that using echo sounders at a frequency of 200 kHz gives good results when searching fish down to depths of 150–200 m. However, available data on sound attenuation in the surface layer and at the level of disturbances are still not precise enough for calculating operation frequencies and acoustic powers of fish-finding instruments.

The efficiency of detecting various forms of plankton depends greatly on operating frequency of an acoustic instrument. In contrast to fish, the acoustic section of which varies only slightly with an ultrasonic frequency, the reflectivity of small organisms depends strongly on frequency (see Section 1.2). It has been experimentally established that strong frequency dependence of the acoustic section of shrimps 4–5 cm long and, consequently, of krill is observed at frequencies of 150 kHz and higher.[11]

The work on fisheries shows that echo sounders operating at comparatively low frequencies (20–30 kHz) register krill concentrations more poorly than those operating at higher frequencies; for example, at 120 or 200 kHz.[12] Recording of krill concentration at lower frequencies is not clear enough, especially with registering small density concentrations, when it is difficult to determine their actual depth and vertical extent. In operating high-frequency echo sounders, recordings of krill concentrations on the echogram are always distinct; the sections of different density are distinguished very easily. Thus, operation frequencies of echo sounders for effective detection of krill and other plankton organisms must be higher than 200 kHz. Detailed investigations of frequency characteristics of various forms of plankton are required for determining more accurately operation frequencies.

PING DURATION

As mentioned previously, a decrease in the ping duration is required to ensure a high-resolving capacity of an acoustic instrument. At a minimal duration, an impulse of typical echo sounders has a filling on the order of 20 periods of the operation frequency; i.e., $\tau_{min} = 20/f$. For example, if $f = 20$ kHz, then $\tau = 1.0$ ms; if $f = 100$ kHz, then $\tau = 0.2$ ms. In regard to these cases, a ping will reach its fixed value.

Maximal impulse duration is used for detecting surface or bottom fish. Short impulses are required when interpreting the readings, for a separate registration of fish in dispersed concentrations, in measuring the target strength of individual specimens *in situ*, and so on. An increase in the ping duration when registering individual fish is not reasonable as it does not affect the values of echo signals.

An increase of the impulse duration in registering dispersed concentrations can only be useful when detecting and clearly registering individual fish against a background of disturbances. It follows from Figure 2.10 that the detection of fish is noticeably improved with an impulse duration of $\tau = 3.0$ ms; with a duration of $\tau = 1.0$ ms, it becomes hard to differentiate the useful echo signals from disturbances. The possibility of narrowing the bandwidth of the receiver appears with an increase in the ping duration as $\Delta f_{opt} = 1/\tau$. This promotes decreasing the energy of noises and better recognition of useful signals against a background of disturbances.

Varying the ping duration in registering fish concentrations gives entirely different results. Thus, with operation on fish concentrations of large extent, an increase of the impulse duration leads to extending an impulse volume; the number of fish in it also grows and the value of an echo signal becomes greater. Such an increase in echo signals will be limited only by the sound attenuation inside a concentration.

In registering dense objects, which are only insignificantly transparent to acoustic impulses (a sea bottom, vessel body and so on), the summary amplitude of echo signals is basically formed as reflections from the area of an object. In these cases, the scattering element will constitute the surface, the reflected waves from which arrive at the point of reception simultaneously. Taking into account that the maximum of a reflection from a ground echo signal is caused by the first impulse volume, it is easy to determine the condition of the maximal use of the acoustic power of an instrument. It may be expressed by the following formula[8]:

$$\tau_{opt} = \frac{2r}{c}\left(\sec\frac{\theta_{eff}}{2} - 1\right) \tag{2.34}$$

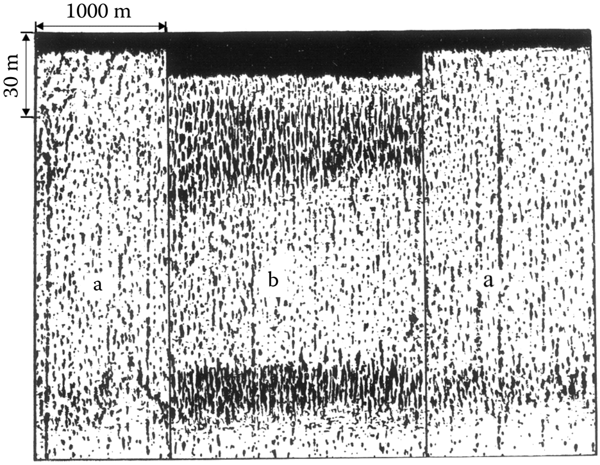


FIGURE 2.10 Recording of dispersed blue whiting in the North Atlantic (range, 150 m; wave height, 6–12 feet): a, $\tau = 1.0$ ms; b, $\tau = 3.0$ ms.

Relation (2.34) shows that, in registering the bottom with an echo sounder, increase of ping duration and sound beam width gives an effect to a certain point, beyond which there is no growth of echo signals because of the summing of reflections of side beams.

For instance, with r = 1500 m and $\theta_{eff} = 10^\circ$, the calculated value from formula (2.34) of ptimal duration of a sounder ping $\tau_{opt} = 8.0$ ms. As the depth decreases, the value of limiting width for the diagram of detecting the bottom abruptly increases. However, formula (2.34) shows that, in regard to fish-finding instruments, τ_{opt} does not usually exceed 20 ms.

Thus, the duration of pings for detecting individual items, concentrations, or the bottom should be different; their values may vary from 0.1 up to 20 ms.

THE GAIN OF AN AMPLIFIER

The maximal sensitivity of an amplifier is determined by the level of disturbance (I_n). The admissible gain, which can be used with a given level of disturbance, can be expressed as[13]:

$$\mu_{max} = U_{min}\left(\chi\delta_s\sqrt{\rho c I_n}\right)^{-1} \tag{2.35}$$

where χ is the sensitivity of a transducer in receiving, µV/Pa.

It was mentioned in Section 1.5 that the values of the coefficient of recognition δ_s and the threshold level of detection U_{min} depend, largely, on the methods of indication and treatment of echo signals. As to indicators of an acoustic instrument, the admissible value of coefficient δ_s is determined by the number of echo signals registered. Calculations in Section 1.5 show that when more than five signals arrive from the target, $\delta_s = 1.4$. With an indication of echo signals on a display or printer, the value of threshold registration voltage varies within limits of several volts.

The maximal receiver gain taken for designing an acoustic instrument is set with consideration of the most favorable possible conditions of its exploitation (assuming calm weather and only slight drift of a vessel), when the disturbing noises are minimal. The intensity of noises on a transducer at operation frequencies of 20–30 kHz on a vessel stopped in calm weather can be on the order of 10^{-12} W/m^2 and less. At these frequencies, modern ceramic transducers have a sensitivity χ on the order of 10^3 μV/Pa and more.

Formula (2.35), with the use of all the parameters considered, demonstrates that the values of the maximal gain must be on the order of 10^7. Experience with use of the equipment shows that such a gain is sufficient for detecting dispersed fish at great depths as well as small plankton concentrations.

SEARCH RANGES OF INDICATORS

One of the major requirements in choosing the main ranges of an echo sounder is the registration of individual items within the water layer and near the bottom. It is generally accepted that in order to detect an individual fish against a background of impulse disturbances it is necessary to receive from it at least three echo signals. Relation (2.27) illustrates that the repetition frequency of echo sounder pings in this case should be[8]

$$f_{imp} = \frac{3v_{vess}}{r\theta_{long}} \tag{2.36}$$

This formula shows that for reliable detection of fish at shallow depths, sufficiently high repetition frequency is required; therefore, a large scale of registration is needed.

Experience shows that in fisheries regions echo sounders poorly register fish dispersed near the bottom and the use of large-scale indication does not improve the situation because the fish are masked by ground recordings (see Section 4.1). It has been established that, in order to detect demersal fish by a small-range echo sounder (200–300 m), the vertical scale of registration is sufficient to be 0.5–0.7 m/mm and in middle-range echo sounders (500–600 m), about 1.0 m/mm. This means that with screen display height or width of printer paper on the order of 200 mm, the search range for small distance echo sounders may be 100 mm, and for middle distance, 200 mm. The depth of range phasing is chosen to guarantee the registration of fish concentrations to the limiting detection depths for these kinds of echo sounders.

In determining the main ranges of an echo sounder, the disturbing effect of false recordings should be taken into consideration, which can be registered on the echogram by the second and further moves of a pen or beam. In order not to allow the false recordings to darken the working area of the echogram, two close ranges are used; by switching to another range, false recordings disappear or are registered at a different depth.

To control simultaneously the great thickness of water, small-scale view ranges are used. The choice of the range is determined by the type of echo sounder distance. However, it is difficult to detect dispersed fish on the view range, especially at surface layer or near the bottom. In these cases, in surveying concentrations, which are subjected to fishing, registration by layer with the help of an electronic expander of recordings is used in addition to the view and search ranges.

The quality of fish registration on the echogram depends not only on the range chosen, but also on the speed of horizontal scanning in the display or paper speed through the printer. An analysis of many recordings has shown that the speed of scanning in the display or paper speed through the printer v_p in the main search range of an echo sounder should be as follows[8]:

$$v_p = 0.5d \text{ (mm/imp)}$$

or

$$v_p = 0.5df_{imp} \text{ (mm/min)} \tag{2.37}$$

where d is the width of one track on the display or the printer paper; d is approximately equal to 0.3 mm.

When using an echo sounder for navigation purposes or for tentative surveying of fisheries areas, the following paper speed is required

$$v_p = 0.2d \text{ (mm/imp)}$$

or

$$v_p = 0.2df_{imp} \text{ (mm/min)} \tag{2.38}$$

With aimed fishing for detailed and precise registration of concentrations detected by an echo sounder

$$v_p = d \text{ (mm/imp)}$$

or

$$v_p = df_{imp} \text{ (mm/min)} \tag{2.39}$$

In sonar, for reliably monitoring fish schools while approaching them

$$v_p = d + 0.2 \text{ (mm/imp)}$$

or

$$v_p = (d + 0.2)f_{imp} \text{ (mm/min)} \tag{2.40}$$

On the basis of conditions (2.37), (2.38), and (2.39), the following limits of the speed of scanning and paper speed could be recommended for the main ranges of echo sounders, from 0.06 up to 0.30 (mm/imp).

REFERENCES

1. Urick, R.J., *Principles of Underwater Sound*, McGraw-Hill, New York, 445, 1975.
2. Kalikhman, I.L., *Investigation of Probability Characteristics of the Range of Detection of Fish Concentrations by Acoustic Instruments*, VNIRO, Moscow, 14, 1977 (in Russian).
3. Borisenko, E.S., Bondarenko, V.M., Stefanov, S.R., and Chistoserdov, Yu.P., The investigation of sound attenuation in the sub-surface layer of the ocean by the autocirculation method, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series “Fishery Acoustic Problems,” Yudanov, K.I., Kalikhman, I.L., Shabalin, V.N., Eds., VNIRO, Moscow, 136, 1983 (in Russian).
4. Borisenko, E.S., Investigation of losses of the acoustic energy in water-fish medium, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series “Fishery Acoustic Problems,” Yudanov, K.I., Kalikhman, I.L., Bondarenko, V.M., Eds., VNIRO, Moscow, 32, 1989 (in Russian).
5. Borisenko, E.S., Results of experimental measurements of the excessive sound attenuation in aerated layers of the ocean, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series “Fishery Acoustic Problems,” Yudanov, K.I., Kalikhman, I.L., Bondarenko, V.M., Eds., VNIRO, Moscow, 40, 1989 (in Russian).
6. Kalikhman, I.L., Tesler, W.D., and Yudanov, K.I., Methods of determining the density of fish concentrations, in Meeting on Hydroacoustical Methods for the Estimation of Marine Fish Populations, 25–29 June 1979, II: Contributed Papers, Discussions, and Comments, Suomala, J.B., Ed., The Charles Stark Draper Laboratory, Cambridge, MA, 533, 1981.
7. Kalikhman, I.L., Bondarenko, V.M., and Protaschuk, V.A., Investigations of statistical characteristics of echo signals from model concentration of various density, *Fisheries*, 8, 47, 1980 (in Russian).
8. Yudanov, K.I., *Interpretation of Echograms of Hydroacoustic Fish-Finding Instruments*, Vilim, E., Trans., Keter Press, Jerusalem, 101, 1971.
9. Yudanov, K.I., Choice of acoustic power and working frequency of fish finding instruments, *Fisheries*, 10, 46, 1977 (in Russian).
10. Turin, A.M., Stashkevich, A.P., and Taranov, E.S., *Principles of Hydroacoustics*, Sudostroenie, Leningrad, 295, 1966 (in Russian).
11. Andreeva, I.B. and Samovol’kin, V.G., *Sound Scattering by Sea Organisms*, Agropromizdat, Moscow, 102, 1986 (in Russian).
12. Yudanov, K.I., The possibility of detection and quantitative estimation of krill concentrations by acoustic instruments, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series “Fishery Acoustic Problems,” Yudanov, K.I., Kalikhman, I.L., Bondarenko, V.M., Eds., VNIRO, Moscow, 36, 1983 (in Russian).
13. Yudanov, K.I., *Acoustic Fisheries Prospecting*, Sudostroenie, Saint-Petersburg, 187, 1992 (in Russian).

3 Search for Commercial Items with Acoustic Instruments

The search is a step of the process of reconnaissance, which represents a number of operations aimed at detecting commercial concentrations. Research and fishing vessels perform an acoustical search to an equal degree. Fishing vessels, with the help of acoustic technique, perform the local search in commercial regions to determine the presence of significant fish concentrations.

In the second part of the 20th century, one of the main tasks of research vessels was the search of new and poorly developed regions and items of fisheries. Special expeditions comprised of several vessels were organized for this purpose. At the present time, unexplored areas in the World Ocean are few and the detection of new commercial regions is scarcely probable; the expenses for such searches continually grow.

The conservation of biological resources and rehabilitation of overfished populations in the main oceanic regions are now more important tasks than the search for commercial areas and items. Therefore, research vessels first ensure the control of the state of biological resources and fishing conditions. For this purpose, acoustic investigations and passing observations are carried out. Searching operations are only conducted when anomalous climatic conditions cause the distribution of commercial concentrations in known regions to strongly differ from the regular one.

The possibilities for search and detection, as well as of the interpretation and estimation of commercial concentrations, depend greatly on the character of distribution of marine animals. Therefore, before considering the tactics of the acoustic search, let us examine the general forms of distribution of fish and other aquatic organisms.

3.1 SHAPES OF DISTRIBUTIONS OF COMMERCIAL ITEMS AND THEIR REGISTRATION BY ACOUSTIC INSTRUMENTS

The distribution of aquatic animals can be systematized within the species group, by the water area and by depth.

THE DISTRIBUTION WITHIN A SPECIES GROUP

Observations of marine organisms with the help of acoustic instruments, as well as from aircraft and underwater apparatus, show that specimens of one species may be grouped in different ways. The structure of a species group, to a great extent, depends on the item's behavior and its biological conditions. This thesis relates, to an equal degree, various commercial fishes and non-fish items (shrimps, squids, jellyfish, and other forms of plankton). Each species may have the following shapes of distribution: dispersed, in schools, or in concentrations.

The distribution is understood to be *dispersed* if individual specimens keep separated from one another; they are not connected by a joint behavior. A dispersed distribution is observed with many mass fish species immediately following their spawning, when fish collapse and are in a passive state. Commercial items may maintain dispersal within the period of feeding if food organisms are distributed over a wide area.

Dispersed behavior is most typical for large fish, namely cod, haddock, sea perch, swordfish, tuna, sharks, and whales. Underwater observations show that demersal fish such as wolffish, skate, and bullhead usually maintain their individuality. Herring, anchovy, sprat, and other mass pelagic species much more rarely present such a distribution. For detecting dispersed items, acoustic instruments must have a high sensitivity, especially when registering individual fish at great depths.

The distribution is understood to be a *school* or *shoal* if commercial items within it maintain compact groups. G.V. Nikolsky understands a school as a group of fish of close biological state and age, united by common behavior and orienting upon each other.[1]

Pelagic fish, feeding on plankton, very often have a schooling way of life. The schooling distribution is typical during a long period of life for various herring, sardine, sprat, and other planktivorous fish. For demersal fish, schooling behavior is not widely distributed.

Fish gather into schools during times of migration, as well as within the period of intensive fattening. The dimensions of schools during the fattening depend, to a great extent, on the character of distribution and concentration of food organisms. The size of schools during migration depends on the rate of fish motion. Fish schools assume a streamlined shape while moving. Schools are not large in a rapid movement. They become much larger at fish resting places along the migration route. Schools attain large dimensions during spawning migrations, especially upon arriving at the spawning grounds.

School shapes and sizes may vary strongly for various reasons. Observations show that a school can abruptly change its shape, even for a short period of time. Larger schools are often crushed into smaller ones. Numerous acoustic observations show that the shape of schools can greatly change during vertical migrations. As a rule, schools extend in the vertical direction during the morning ascent. At short stops, the configuration of schools can change again: the vertical dimensions decrease and the horizontal ones increase. A larger school disintegrates into a smaller one during the rise to the upper layers of the water.

Such an insignificant factor as the bottom relief also affects the shape of schools. Observations in the English Channel show that schools of herring have a clear-cut shape in cases when they are located over an even bottom. If a school is situated over a cavity or ridge, its borders are more diffuse.

The number of fish in a school may also vary within large limits. The schools of gadoid fish usually include dozens or even hundreds of specimens, while schools of herring can aggregate many thousands of fish.

A *concentration* is the unification of schools or dispersed fish, forming for various reasons. Often, different schools contact each other so closely that this leads to their partial or complete mixing. As a result of such a mixing of schools, the common behavior breaks down in a concentration. In this sense, fish concentrations are, as it were, an intermediate between a dispersed distribution and a school.

Echo sounder observations show that schools mixing in the internal part of a concentration are usually more clearly distinct than those at its borders. For this reason, an echo sounder registers schools or dispersed fish on the borders of a concentration depending on the distribution form prevailing when forming a concentration. But, there are cases when no mixing at all occurs. The observations showed that cod of the Barents Sea, during their feeding period on capelin, keep on the periphery of capelin schools without mixing with them.

The formation of concentrations is strongly connected to specific physical or geographical conditions. A concentration can be caused by abrupt changes in the media conditions along migration routes. These may be such phenomena as a temperature gradient, current rotations, concentration of food organisms, and other reasons. Concentrations are observed in certain areas of the sea during fish fattening, spawning, and wintering.

The shape and dimensions of concentrations can vary over great ranges. It depends on the fish abundance and the conditions of their habitation in each specific area of the sea. In some cases, a concentration can be large and registered by acoustic instruments as a narrow band of an extent of dozens or even hundreds of miles. In the others, the area of concentration may be rather limited, but it can have a very large vertical extent.

DISTRIBUTION BY WATER AREA

Distribution of commercial items by water areas is determined by the physical conditions in the water body, the food sources, the abundance of items, their physiological state, and so on. The distribution can greatly vary depending on the above conditions. As a result, the water area of the fish distribution during some periods includes thousands of miles, while at other times the same species concentrates on a very small part of the water area.

With consideration of the above peculiarities, one can distinguish the following types of distribution by water area: diffuse and local.

A distribution is called *diffuse* if commercial items maintain their pattern over a large area of the water. This type of a distribution is especially typical during the period of fish feeding. Such a distribution can also be observed during the spawning season in the case of large spawning grounds. Of course, a necessary condition of a distribution for organisms over a considerable area is an abundance of them.

A *local* distribution takes place if, for some reasons, fish have to concentrate within a limited part of a sea which is most favorable for their habitation.

Under a diffuse or local distribution, marine organisms can maintain three types of interspecies groupings: dispersed, schooled, or concentrated. As a result, the following variants of distribution take place: diffuse dispersed, local dispersed, diffuse schools, local schools, diffuse concentrations, and local concentrations.

The structural scheme of the forms of distribution is presented in Figure 3.1.

A *diffuse dispersed* distribution over a large area is observed rather often in such demersal items as cod, haddock, or sea perch during the period of their fattening. The areas occupied by cod or perch in these cases, for example, in the Barents Sea as well as near Newfoundland Island, make up thousands of square miles. Pelagic fish, for instance, scomber, horse mackerel, herring, and others, may also be distributed this way. Thus, in the Baltic Sea, there are periods within which, with the favorable distribution of food organisms and corresponding physical conditions, herring maintain dispersal over large areas of the sea.

Acoustic instruments register fish and other organisms distributed dispersedly as a great number of individual specimens. A typical recording of a dispersed distribution of cod on the echogram of the echo sounder is shown in Figure 3.2. As is seen from the figure, individual fish are recorded clearly and separately throughout the entire water column, right down to the bottom.

A dispersed concentration of large fish (cod, sea perch, and others) may be of interest for fisheries. Substantial catches with such a distribution of small fish can be obtained only by using drift nets or traps set along the currents.

A *local dispersed* distribution of marine organisms is observed rather rarely. Such a distribution is observed under unfavorable habitation conditions and with small fish abundance. An example of a local dispersed distribution is the distribution of cod in the Baltic Sea, when fish kept separate over comparatively small parts of the sea because of an unfavorable oxygen regime, which existed in many cavities for several years. This distribution is characteristic for very large animals only (whales, dolphins, or sharks).

A *diffused school* distribution is the most typical for marine pelagic organisms within their period of fattening. Within this period, fish concentrate in small schools

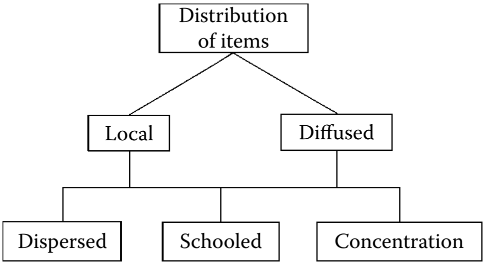


FIGURE 3.1 The shapes of distribution of aquatic animals.

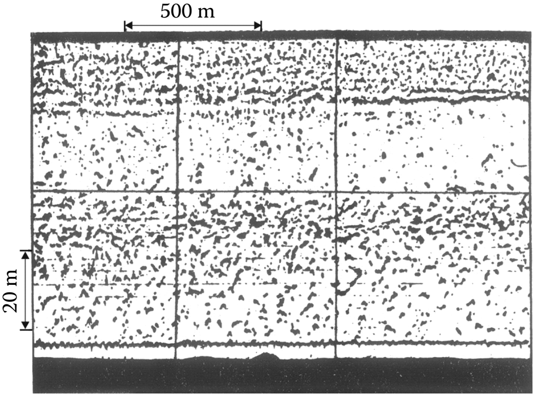


FIGURE 3.2 The dispersed fish distribution: recording of cod in the region of the island Novaya Zemlya (range, 75 m).

dispersed over a large area. A typical picture of the school distribution is given in the echogram (Figure 3.3). Sprat, herring, and many other fish are registered this way. Schools of small specimens of Antarctic krill give analogous recordings.

To trawl schooling fish is more difficult than trawling dispersed ones or fish in concentrations. Considerable experience is needed in trawling moving schools during their migrations, when the densely grouping fish are sensitive to the approach of a trawl.

A *local school* distribution is usually observed along the routes of movement of pelagic fish, in the places of abrupt deepening, in regions of contact of warm and cold currents, and near areas of plankton bloom. Schools linger and accumulate during fattening, spawning, and wintering migrations at these locations.

Local schools are of great interest for fisheries. Separate schools often attain large dimensions and are made up of dozens or even hundreds of specimens. Large schools are usually called *shoals*. Each shoal is a commercial item for trawl or purse

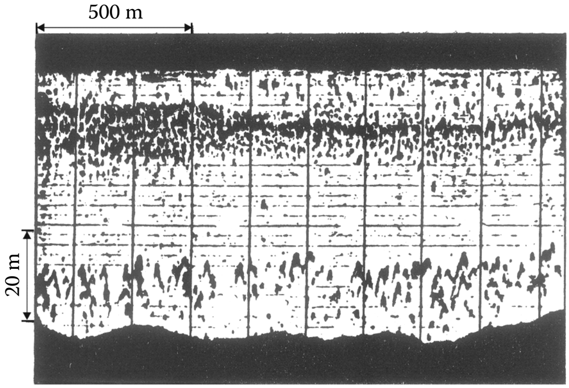


FIGURE 3.3 Diffused schooled fish concentration: recording of herring in the North Sea (range, 75 m).

seine. When moving to spawning grounds, schools of various herring (North Sea, Far East, Atlantic) may have a diameter of more than 100 meters and produce catches of 50–100 tons. The recordings of such schools resemble comets (Figure 3.4).

Both pelagic and demersal fish form *diffuse concentrations* rather often. Recordings of diffuse concentrations usually appear as long bands at a certain depth (Figure 3.5 and Figure 3.6). The extension of a band may reach dozens or even hundreds of miles. For example, herring and whiting in the North Sea, sea perch in the area of Newfoundland Island, and sprat in the Baltic Sea frequently form such a distribution. Diffuse concentrations do not usually have a high density. Catches on such concentrations are stable but only rarely reach large values.

Diffuse concentrations of great density are rarely observed at present. In the past, when fish came to places of fattening or spawning in great abundance, this phenomenon took place. Herring in the Barents Sea created concentrations of great density arriving at the shore. Large horse mackerel in the Black Sea also formed

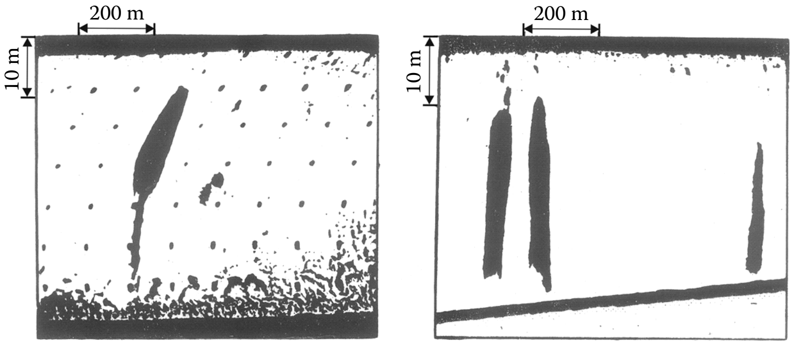


FIGURE 3.4 Local schooled fish concentration. Left: recordings of herring before spawning in the Baltic Sea (range, 60 m); Right: recordings of anchovy schools in the Black Sea (range, 60 m).

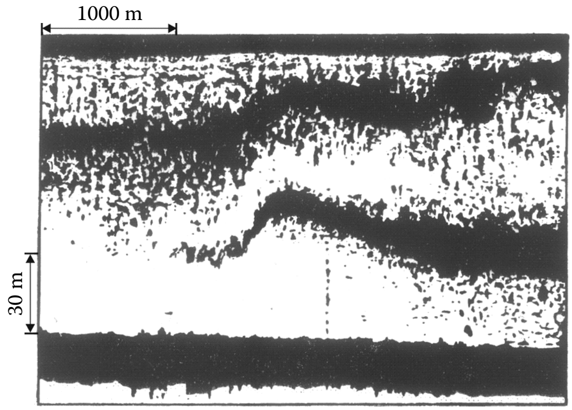


FIGURE 3.5 Diffused fish concentration: recordings of Atlantic mackerel (range, 150 m).

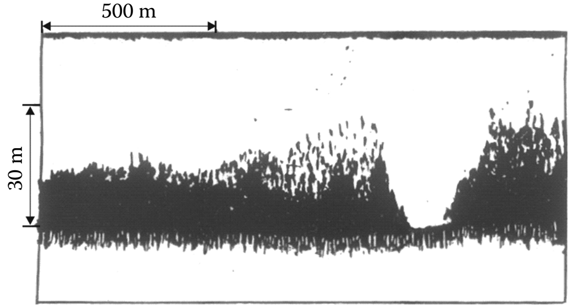


FIGURE 3.6 Diffused fish concentration: recordings of horse mackerel in the Black Sea (range, 300 m).

this kind of distribution. Huge concentrations were typical for Far East herring while coming to the near shore zone for spawning. The catches obtained from these concentrations were especially great.

A diffused distribution is the most typical for plankton and other small marine organisms; it is always observed in near shore waters, as well as in an open sea and registers as one or several layers. The extension of concentrations can reach hundreds of miles. The thickness of layers varies from several meters to hundreds of meters and more. Such concentrations are called sound-scattering layers (SSL).

Sound-scattering layers have been investigated in many seas.[2] They are classified as shallow- and deepwater. Deepwater scattering layers usually take place over depths of more than 500 meters. Even in such a poor populated sea as the Sargasso, we observed scattering layers consisting of concentrations of plankton, shrimps, and different deepwater fish which were registered by the instruments as continuous bands of 100 meters in thickness.

Local concentrations represent aggregations of marine organisms, which are formed in certain sea areas within periods of minimal activity during fattening, spawning, or wintering migrations. In contrast to a local school distribution, these concentrations appear only with mass migrations. Concentrations of especially great density are formed at spawning grounds and on the way to them.

Sea areas favorable for creating concentrations of marine organisms are characterized by the contact of currents and by specific physical and chemical parameters. For example, concentrations of Antarctic krill are formed in areas of rotations of water masses with certain concentration of oxygen, silicon, and phosphorus. Many fish species accumulate in places of elevation of the bottom along temperature gradients. Fish make stops of the longest duration near spawning grounds on slopes of banks and inshore shallow waters.

Local concentrations exist in nearly all water bodies where there are mass commercial fish. Fish capability for creating stable, dense concentrations is very important for fisheries. A fishing fleet works especially efficiently on such concentrations.

DISTRIBUTION BY DEPTH

Besides horizontal movements, marine organisms make vertical migrations over the ocean's depth.[3] Commercial items change the depth of their habitation depending on the physical conditions, such as illumination, water mass mixing, and distribution of food organisms. The distribution depth can vary over great ranges within the life cycle: during some times, items remain distributed throughout the entire water column; during others, a certain range of depths limits the zone of their distribution. It has been noted that larger specimens are often distributed at greater depths as compared with smaller ones.

Temperature conditions greatly affect vertical migrations of marine animals. Irregularity in the temperature distribution by depth, and especially abrupt temperature gradients, may strongly limit the zone of vertical distribution of items, promoting their concentration at several depths. For this reason, acoustic instruments often register concentrations as one or several layers at certain depths.

Through the use of acoustic technique, extensive material on the vertical distribution of marine organisms in various water bodies has been collected. Peculiarities of vertical distributions of pelagic and demersal fish at different times have been established. In particular, acoustic instruments revealed the significant vertical migrations of cod, haddock, or sea perch; i.e., fish, that were considered as a group to be demersal. It has been established that these fish, in addition to a long residence period near the bottom, are located a significant amount of time in intermediate layers of the water.

A characteristic peculiar to vertical migrations is the fast transformation of one shape of distribution to another. A dispersed distribution can be transformed to schools, schools to a concentration, and so on. For instance, during the daytime, cod may be located near the bottom as a concentration, while at night they have a dispersed distribution after rising to upper water layers. Within the period of fattening, herring may form as a concentration during daytime but, during the evening, they are grouped into schools and then they disperse near the surface. At night, fish are distributed in the upper layers rather evenly throughout the water area. At dawn, when fish begin to see each other, they gather into schools. The morning descent is also performed in schools.

Before spawning, herring and some other fish behave slightly differently: they remain as concentrations during vertical migrations and their movements are accomplished slowly. In general, as shown by echo sounder observations in various water bodies, the greatest variety of fish distribution forms are observed during the fattening period, while the least occur during spawning.

In the presence of mixed fish concentrations, a different character of vertical migration for each species and its separate populations leads to various fish distributions during their vertical movement. For example, we observed a complicated picture of the vertical migrations of herring in the North Sea within certain periods. It may happen that in the evening, simultaneous with a slow concentration movement throughout the water column, rising of schools to the surface takes place. An analogous phenomenon also occurs during the morning descent of herring (Figure 3.7). Such mixed vertical migrations result from the fact that different populations of cod, with various physiological conditions, gather in the same region.

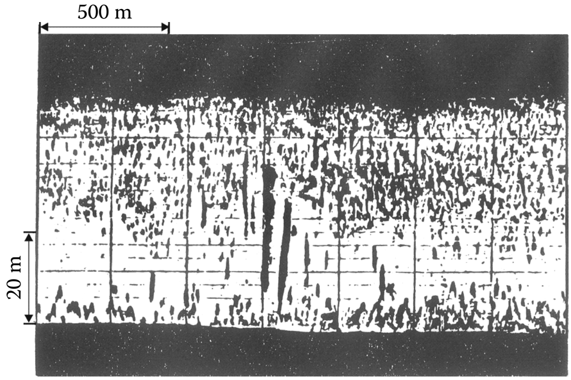


FIGURE 3.7 Recording of the morning sinking of herring in the North Sea (range, 75 m).

Daily vertical migrations of fish and other marine items are connected with the alternation of day and night. For example, the distribution of most planktivorous fish within the water column depends strongly on illumination.[3] Fish sink in depth with the sunrise. In cloudy weather, they rise to the surface again. Even at night, fish behave differently: by moonlight, they disperse to a greater extent than on dark nights.

Scattering layers of noncommercial items also have well-pronounced daily vertical migrations. During daylight, they may be distributed down to a depth of 500 meters, and toward the evening, they move to the upper layers of the water. Typical to that during vertical migrations is a division of one concentration into several layers, segregated by species and length composition (Figure 3.8). Sometimes, several layers are observed during daylight. Without proper experience, acoustic recordings of such scattering layers can be easily taken for fish.

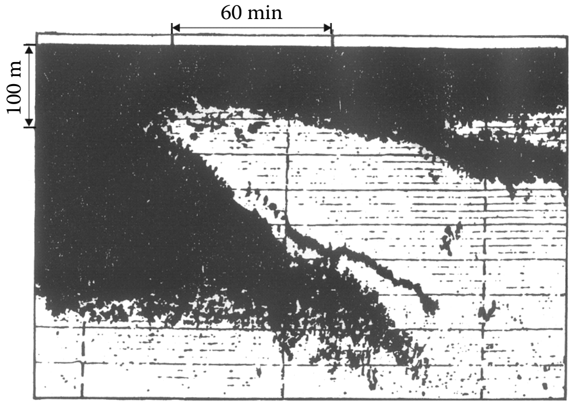


FIGURE 3.8 Recording in the vessel drift of the morning sinking of marine organisms in the Sargasso Sea (range, 600 m).

Variation of illumination influences the character of migration especially strongly for such demersal fish as cod and perch. In daylight, sea perch near Newfoundland Island compress themselves toward the bottom; during cloudy weather, they rise up from the bottom. Sometimes, such displacements are observed over several hours and even during the course of one trawling. Observations of the vertical distribution of Barents Sea cod and haddock indicate great daily fluctuations of catches in spring and fall. In summer and winter, i.e., during a polar day or a polar night, there are practically no vertical migrations; therefore, the fluctuations of daily catches are not great.

It follows from the above that the distribution of commercial items substantially affects the results of fisheries utilizing different fishing gears. However, all types of distributions can provide commercial catches. Therefore, it is necessary to ensure the detection of items by acoustic instruments for all types of distributions.

Further on, in analyzing the possibilities of acoustic equipment for a biomass search and estimation, we will widely use the term "commercial concentration." Commercial concentration will be understood to be a grouping of marine animals, distributed dispersedly, schooled, or concentrated, that may be an object of fisheries for a commercial fleet.

3.2 TACTICS OF SEARCH FOR COMMERCIAL CONCENTRATIONS

In searching for concentrations, especially during anomalous years, when great regions of the sea must be investigated, one first tries to find water areas with favorable conditions for habitation of commercial items. For this purpose, background surveys of the regions are carried out. The grid of transects of a survey is located so that it will intersect zones of a supposed contact of currents, depth overfall, and along the general direction of isobaths. A background survey should include, in addition to standard physical transects and stations, acoustic observations with control fishing for an ichthyologic analysis. On the basis of such a background survey, the water areas favorable for formation of concentrations are selected. In these areas, a more detailed acoustic search of commercial concentrations is conducted.

The possibilities of designing a search in a certain region depend, first of all, on peculiarities of the distribution and behavior of commercial items, which are determined by the complex of factors of the habitation medium and can change during the life cycle of animals. Taking this fact into consideration, it is possible to recommend only general statements to be used in designing a search for commercial items.

The region of the search is usually determined by data of fisheries from past years, the bottom relief, hydrometeorological conditions, and so on. In the presence of the contact of different waters, currents, or depth overfalls, the search should be carried out across currents and isobaths. If the temperature distribution is known, transects are located at a certain angle to isotherms. In cases when commercial items rise to the surface at night and are poorly registered by acoustic instruments, the search is conducted during daylight only. The transect direction has to be changed taking into account the roughness of the sea during bad weather because of the adverse influence of sea-generated noises on the signals of fish-finding instruments.

The cited tactical statements and methods allow for specifying the borders of the regions of the search work and determining the general direction of transects. The next important preparatory step of the search is designing the grid of transects for efficient acoustic detection of commercial concentrations.

The determining condition for success of acoustic detection of commercial concentrations is their crossing by search transects. All concentrations, which fall into intervals between transects, form irreversible losses at this step of the search and can be detected only by following scouting work. Therefore, it is obvious that the grid of transects designed directly affects the efficiency of the search survey.

In the practice of designing a grid of transects, permanent compromise solutions have to be found in the following contradictory situation: on the one hand, a denser grid of search transects leads to a higher probability of detecting commercial concentrations; on the other, a denser grid of transects increases the duration and cost of the search work or, with the same expenditures and duration of work, decreases the dimensions of the water area studied.

In the present section, we will not discuss questions of commercial efficiency of the search. Let us consider theoretical and practical statements connected to the efficiency of the search with the help of an echo sounder.

The probability of intersection of commercial concentrations by transects can serve as a convenient characteristic of the efficiency of search surveys. Buffon, a known 18th-century French naturalist, first successfully solved an analogous problem on geometrical probability. He determined the probability of intersection of parallel lines by a randomly located segment of straight line. This problem was further solved, in a generalized form, by the French investigator of the 19th century, Barbier, which proved that the probability of intersection by the line of the figure having the maximal dimension D,[4]

$$p = \Phi/(\pi D) \tag{3.1}$$

$$D = \Phi/(\pi p) \tag{3.2}$$

where Φ is the perimeter of the figure.

It follows from relation (3.1) that, regarding the search for commercial concentrations by echo sounder, it is necessary to know the geometric parameters of a concentration and of the grid of transects for determining the probability of its detection.

Geometric dimensions and configurations of commercial concentrations can vary greatly. In addition, they vary strongly depending on the biological state of items and environmental factors. Therefore, they can be considered as random variables. As a rule, concentration shapes are so complicated and diverse that it is impossible to directly systematize them by geometric parameters. As a way out of this difficulty, real concentrations should be approximated by idealized concentrations of round or elliptic shape equal by area.

A circle usually approximates the contours of commercial concentrations. The approximation by an ellipse with a certain degree of extension is possible if there is confidence that the item distribution in the area under study has a pattern stretched in a known direction, for instance, at the border of currents, within a gradient zone, at the depth overfall, along certain isobaths or isotherms, and so on.

If the shape of a concentration is considered round, then relation (3.2) takes its simplest form:

$$D = l_{con}/p \tag{3.3}$$

where l_{con} is the diameter of a concentration.

In regard to an elliptic concentration, relation (3.2) assumes the following form:

$$D = \left[1.5\left(l'_{con} + l''_{con}\right) - \sqrt{l'_{con} l''_{con}}\right] / \left(2p\right) \tag{3.4}$$

where l'_{con} and l''_{con} are the dimensions of the large and small axes of the ellipse.

It appears that the cited relations permit solving the problem of determining the optimal distance between transects when detecting commercial concentrations of a round shape. However, the practical application of relations (3.3) and (3.4) is limited, as they do not allow judging about the degree of intersection of concentrations with the ultrasonic beam of an acoustic instrument.

Experience shows that, when registering the border of a concentration, it may be considered as noncommercial and, then, one may pass it by; therefore, for ensuring the reliability of the detection of a concentration, it is necessary to intersect a significant part of it. Taking this into account, the calculation of the grid of transects, based on the solution of the Buffon–Barbier problem, boils down to the application of corresponding formulas, tables, and nomograms.

Methods of optimizing the grid of the search in geologic reconnaissance of the deposit of minerals are the most highly developed. Taking into consideration that the conditions of the problem of determining the optimal grid of transects coincide with those of acoustic search, we used the main principles and methods of calculating a geologic grid of transects. The calculations are made regarding immovable objects of a search for round and elliptical shapes and a uniform grid of transects. For the case of an elliptical shape of objects, it is assumed that its orientation, to a certain extent, is known: transects are carried out perpendicularly to the direction of the maximal stretching of an object with a maximal error of ±30°.

Under the condition that the major axis of an elliptical object l_{con} is less than the distance between transects D, the interval of intersection of the object by a transect can be expressed as (Figure 3.9)

$$l_{cr}(x,\theta) = 2l'_{con} / \left(a l''_{con}\right) \sqrt{a^2 \left(l''_{con}\right)^2 /4 - x_i{}^2} \; ; \; a^2 = \sin^2\theta + (l_{con}/l_{con}')^2 \cos\theta \tag{3.5}$$

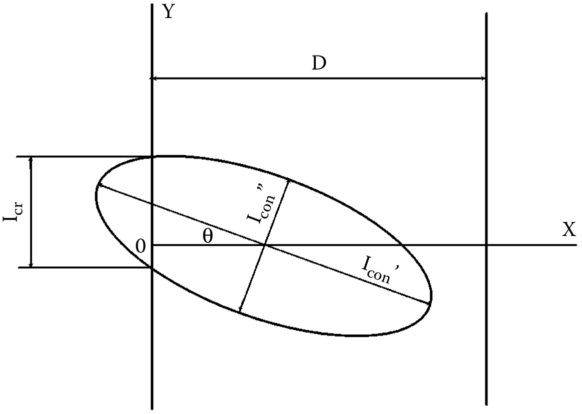


FIGURE 3.9 Scheme of crossing an object of elliptic shape by parallel transects.

where θ is the angle of the orientation of the elliptical object in relation to the direction of a transect and x_i is the coordinate of the center of the object.

The probability of intersecting the elliptical object by a transect at the segment l_{cr} with a fixed angle θ is determined by the following dependence:

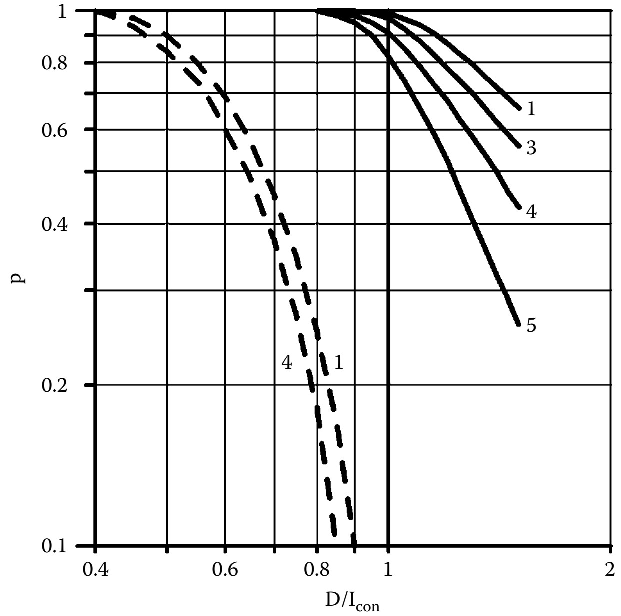
$$p(\theta) = 2/(Dl_{cr})\left[l_{cr}x_i - \int_0^{x_i} l_{cr}\left(x,\theta\right)dx + \left(D - al''_{con}\right)/D\right] \tag{3.6}$$

Unknown values of probabilities p(θ) for various locations of the ellipse are found through bulky numerical integration of expression (3.6) at the interval of values (0, 30°) by the formula of Simpson. The probabilities p(θ) for the case when the unknown object is intersected by two transects are calculated in an analogous way.

In solving the problem of the search for commercial concentrations, we used the results of calculations presented as tables, graphs, and nomograms.[5] The graphs of probability of intersecting commercial concentrations of a round and elliptical shape by one or two transects are shown in Figure 3.10. It is assumed in calculations that the variation in locating elliptical objects is possible within the range of $\theta = \pm 30°$. The graphs are given for various lengths of intersection, expressed as a part of the parameter of the grid of transects D and the extent of stretchiness of concentrations ($b = l_{con}/l_{con}$). Along the abscissa axis, the distances between transects are given, expressed as units of l_{con}. Along the ordinate axis, the probability values are shown.

The cited graphs make it possible to determine the optimal grid of transects for given dimensions of commercial concentrations, the interval of their intersection, and the probability of detection.

It is also possible to solve the inverse problem, objectively characterizing the reliability of investigating a region, estimating the degree of authenticity of the



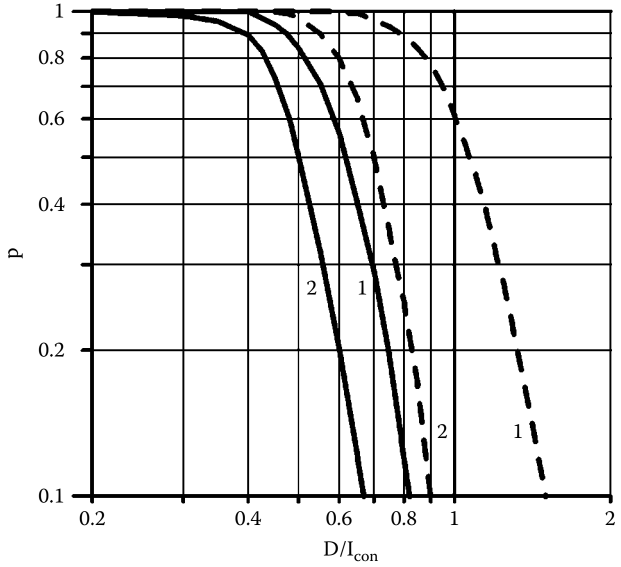


FIGURE 3.10 Graphs of probabilities of crossing objects of various shape by the grid of parallel transects. Top: the shape is round (solid line, crossing by a single transect; dashed line, crossing by two transects); Bottom: the shape is elliptic (b = 0.1, $\theta = \pm 30°$; dashed line, crossing by a single transect; solid line, crossing by two transects). Numbers correspond to the following relations: 1, $l_{cr} = 0.05D$; 2, $l_{cr} = 0.1D$; 3, $l_{cr} = 0.2D$; 4, $l_{cr} = 0.3D$; 5, $l_{cr} = 0.5D$.

results of surveys conducted earlier taking into consideration the geometrical parameters of concentrations revealed and the density of the grid of transects.

For determining an optimal grid of transects, an *a priori* estimate of the dimensions of commercial concentrations is necessary. It is quite obvious that, in designing the search, an orientation towards detecting all concentrations should not be made, as this would lead to an excessively dense grid of transects and, consequently, to a great volume of work with a resulting increase in cost. Clear requirements as to dimensions of objects, the value of the interval of intersection and the probability of detection should stand as the base of designing a search.

In a traditional commercial region, the characteristic dimension of commercial concentration should be known for each period of fisheries; it is determined from the results of acoustic surveys conducted over a number of years. If no acoustic surveys have been carried out within the region of search, it is desirable to search for a clear enough analogy with some well-studied region and to use this for making judgments on the character of distributions and concentration dimensions. When working in weakly studied regions, one may get an idea about dimensions of "typical" concentrations from the condition of their commercial significance ensuring a profitable catch.

It is shown in Section 8.1 that the commercial significance of concentrations (in tons/hour), i.e., the values of possible catches, is calculated from the following formula:

$$Q = 2.9 \times 10^7 K_Q W_{trawl} \rho_{int} / L_{vert} \tag{3.7}$$

where K_Q is the coefficient of catching ability of trawls used in the fisheries; ρ_{int} is the area density of a concentration within the layer of trawling, tons/mile^2; L_{vert} is the vertical opening of a trawl or the thickness of a layer, m; and W_{trawl} is the technical productivity of a fishery complex, m^3/hour;

$$W_{trawl} = 1.85 \times 10^3 L_{vert} L_{hor} v_{vess} \tag{3.8}$$

where L_{vert} and L_{hor} are the vertical and horizontal openings of a trawl, m; and v_{vess} is the speed of a vessel's movement in trawling, knot.

The extension of a concentration l_{con} (in miles), in which the commercial significance is estimated, is determined as

$$l_{con} = v_{vess} t_1 \tag{3.9}$$

where t_1 is the time, equal to one hour.

Substituting (3.7) into (3.8) and (3.8) into (3.9), after transformations we obtain the following relation:

$$l_{con} = \frac{1.85 \times 10^3 Q t_1}{K_Q L_{hor} \rho_{int}} \tag{3.10}$$

It follows from relation (3.10) that the minimally acceptable dimension of a commercial concentration in a weakly studied region can be determined by tentative characteristics of the area concentration density within the zone of fishing ρ_{int}, the commercial significance of a concentration Q, the values of the openings of a trawl used L_{vert} and L_{hor}, and the coefficient of its catching ability K_Q. The mentioned information is received from preliminary acoustic observations and control fishing in the region under investigation.

If, for example, the horizontal opening of a trawl $l_{hor} = 30$ m, the coefficient of its catching ability $K_Q = 0.2$, the density of a concentration within the zone of fishery $\rho_{int} = 200$ tons/mile^2, and the commercial significance Q = 5.0 tons/hour, then substituting these values into formula (3.10), we obtain the minimally acceptable dimension of a concentration for fisheries in the given region:

$$l_{con} = \frac{1.85 \times 10^3 \times 5.0 \times 1.0}{0.2 \times 30 \times 200} = 7.7 \text{ miles}$$

Depending on the population quantity and the character of its distribution, the diameter of a concentration may be from several miles to dozens of miles. For detecting commercial concentrations, which can be approximated by a circle, it is enough to intersect them with a single search transect. An intersection by two and more transects is required when searching for concentrations of elliptical shape. In any case, the probability of detection of commercial concentrations should be high enough - no less than 0.9.

The extension of the interval of intersection is set on the basis of commercial significance and structure of concentrations. Minimally acceptable values of concentration density and the thickness of their recording can be taken as criteria for its choosing. In order to ensure the possibility of making a decision on the commercial significance of a detected concentration during the search, the minimal area concentration density within the layer of fishing should be no less than the determined value. For instance, the density of a commercial concentration of krill should be no less than 200 tons/mile^2 (with $l_{vert} = 20$ m), that of blue whiting no less than 150 tons/mile^2 (with $l_{vert} = 60$ m), and so on.

The extension of recordings of commercial items along the length of the interval of intersection should be different for various shapes of distribution of concentrations. Practice shows that, in designing a grid of transects regarding the search for concentrations consisting of dense schools or shoals, the overall extension of such commercial items along the interval of intersection should be no less than $l_{ext} = 0.05$ miles. The interval of intersection is usually expressed through the coefficient of filling of schools on transects $K_{fill} = l_{ext}/l_{cr}$; that is, $l_{cr} = l_{ext}/K_{fill}$. If the search is designed for dispersed concentrations distributed over great enough expanses of the water area, then the interval of intersection of such a commercial concentration should be no less than half a mile; that is, $l_{cr} = 0.5$ mile.

It was assumed in all the previous considerations that the grid of transects could be designed without taking into account the detection range of an acoustic instrument in a direction perpendicular to the vessel motion in the horizontal plane. This assumption is true with regard to echo sounders as the diameter of their detection range is always smaller than the distance between transects. However, with the search for concentrations by sonar, the detection range of which is commensurable with the distance between transects, the situation is different. In this case, the distance between transects should be increased by double the detection range of the sonar.

Let us return to the determination of the grid of transects according to the assumed dimensions of commercial concentrations taking into account the extension of the interval of their intersection and the probability of detection. In using echo sounders, the values of D are identical to the distance between transects, while with sonar they should be increased by the value of a double detection range of an instrument r_{max} (Figure 3.10). This circumstance should be taken into consideration when performing practical calculations. Let us consider examples of such calculations with the use of the mentioned graphs.

EXAMPLE 1

Let the diameter of a significant fish concentration of round shape l_{con} = 10 miles. Assuming that the probability of its detection in carrying out one transect p = 0.95 and the extension of the interval of intersection l_{cr} = 0.05D, from the right graph in Figure 3.10, top, we obtain D/l_{con} = 1.1. This means that in using an echo sounder, the distance between transects $l_{sounder} = 1.1 \times l_{con} = 1.1 \times 10 = 11$ miles. If sonar with detection range r_{max} = 1.5 miles is used, then the distance between transects $l_{sonar} = l_{sounder} + 2r_{max} = 11 + 2.0 \times 1.5 = 14$ miles.

EXAMPLE 2

A commercial concentration of elliptical shape has been detected by two transects. The extension of a concentration by the major axis is l_{con}' = 15 miles while by the minor axis l_{con}'' = 1.5 miles; that is, the extent of stretchiness of a concentration b = 1.5/15 = 0.1. Assuming the probability of its detection when carrying out one transect p = 0.90 and the extension of the interval of intersection l_{cr} = 0.1D, from the left graph in Figure 3.10, bottom, we obtain D/l_{con} = 0.4. This means that in using an echo sounder, the distance between transects $l_{sounder} = 0.4 \times l_{con}' = 0.4 \times 15 = 6.0$ miles. If sonar with a detection range r_{max} = 1.5 miles is used, then the distance between transects $l_{sonar} = l_{sounder} + 2r_{max} = 6.0 + 2.0 \times 1.5 = 9.0$ miles.

The method considered for calculating the optimal distance between transects is approximate, as the assumption that *a priori* concentrations taken have a continuous spatial distribution is true only in rare cases. Practice shows that the spatial distribution of commercial concentrations is patchy; each patch consists of comparatively small separate aggregations of various dimensions. It is clear that it is impossible to determine the average geometric probability of their detection without accounting for the length of the series of concentrations. This, in turn, does not allow us to estimate the efficiency of the search of all unknown concentrations located within the area of an investigated region.

As was already mentioned, in designing the grid of transects, it is impossible to orient on each comparatively small concentration as, for its reliable detection by an echo sounder, the distance between transects should be of the order of the dimension of a concentration (Figure 3.10). Unfortunately, the limits of time and the dimensions of commercial regions require us to carry out searches using sparser grids of transects. It should be taken into account that, if the distance between transects is chosen equal to nl_{con} (where l_{con} is the diameter of a concentration), then in searching with an echo sounder, about 1/n of all concentrations located in the investigated region will be detected.[5]

It is possible to estimate the general probability of detecting at least one of a group of concentrations of approximately the same dimensions from the following formula:

$$p_{group} = 1 - (1 - p_1)^m \tag{3.11}$$

where p_1 is the probability of detecting one concentration and m is the number of concentrations in the region under study.

For example, suppose that in the region under investigation there must be no less than three concentrations ($m = 3$) and their dimensions $l_{con} = 3$ miles. Working with an echo sounder, if the distance between transects is taken equal to $D = 1.7 \times l_{con} = 5.0$ miles, and the interval of intersection $l_{cr} = 0.2 \times D = 1.0$ miles, then the probability of detecting each concentration $p_1 = 0.5$ (Figure 3.10). In this case, calculated from formula (3.11) the general probability of detecting a group of concentrations $p_{group} = 1 - (1 - 0.5)^3 = 0.875$. This means that the given mode of investigation should ensure high enough reliability of detecting aggregations, indicating the possible presence of a commercial concentration.

A set of statistical data on the distribution of commercial items is required for designing the grid of transects more precisely and for estimating the searching efficiency of surveys. It is expedient to collect such data while carrying out acoustic surveys in various commercial regions.

Knowledge of probability characteristics of commercial concentrations makes it possible to choose the required dimensions of aggregations for determining the distance between transects. From the results of the search work, such characteristics allow for determining which part of concentrations remained undetected, objectively estimating the efficiency of the search in relation to the overall length series of concentrations located in the area of the investigated region. Characteristics of distribution of commercial items are also very important for estimating the catching ability of fishing gears, for improving their productivity.

REFERENCES

1. Nikolsky, G.V., *The Ecology of Fishes*, Barkett, L., Trans., Academic Press, London, 352, 1963.
2. Andreeva, I.B. and Samovol'kin, V.G., *Sound Scattering by Sea Organisms*, Agropromizdat, Moscow, 102, 1986 (in Russian).
3. Zusser, S.G., *Daily Vertical Migrations of Fish*, Pischevaya Promyshlennost, Moscow, 223, 1971 (in Russian).

4. Boev, G.P., *The Theory of Probabilities*, Gostekhizdat, Moscow, 386, 1950 (in Russian).
5. Savinskii, I.D., *Probability Tables for Locating Elliptical Undergroud Masses with a Rectangular Grid*, Consultants Bureau, New York, 110, 1965.

4 Efficiency of Detection of Commercial Items with Acoustic Instruments

With the help of acoustic instruments it is possible to quickly detect commercial concentrations of biological items, determining the distance and bearing, the dimensions and depth of their submersion. Acoustic instruments allow one not only to find but also to maintain contact with detected concentrations, not losing them.

Investigating fishing areas and nearby parts of the sea with fish-finding instruments, it is possible to follow the spatial movements of fish. This is especially important during periods of great activity when the fish move unexpectedly and rapidly. Acoustic instruments allow for selecting denser concentrations within a fishing region and aiming fishing gear at them. Thus, it is possible to increase the efficiency of fisheries in this way.

At present, practically all fishery vessels possess acoustic instruments. However, the possibilities for their use on various bodies of water are far from being the same. Efficiency in detecting commercial concentrations is the main requirement for acoustic equipment. In this sense, the general efficiency of reconnaissance of fish and other marine items strongly depends on the possibilities of acoustic technique.

The possibilities of detecting biological items depend not only on the range, detection zone, and resolving capacity of acoustic instruments, but also on the character of distribution of commercial items. Let us analyze the peculiarities of detecting and registering commercial items in order to clearly imagine the possibilities of acoustic instruments regarding various fishing conditions.

4.1 POSSIBILITIES OF DETECTION OF COMMERCIAL ITEMS BY ECHO SOUNDER

The main reasons for the rapid development of the fish-finding technique are the difficulties of searching for commercial concentrations and the decrease in the productivity of fisheries in traditional regions because of their intensive exploitation and the introduction of 200-mile zones. At present, acoustic instruments for vertical location, echo sounders, are widely used by the fishing fleet. Fish-finding echo sounders allow for detecting commercial concentrations under the vessel bottom, determining their dimensions and depth of submersion.

A great number of types of echo sounders are used on fishing and scientific vessels. For increasing the work efficiency of fisheries and scientific vessels, echo sounders have been developed with a higher sensitivity, wider range of functional possibilities, and finer precision characteristics and indication.

The application of modern electronic technique has allowed for the introduction into practice the numerical treatment of echo signals, memorization of information, and decreasing the influence of disturbances. Different modes of operation are used in echo sounders. Simultaneous indication at two frequencies, expansion of the scale of registration, connection with the bottom, breaking of bottom signals, fixating echo sounder data on a display screen or printer paper, as well as provisions for navigation instrumentation, temperature sensing, and other information required for search and fisheries are all now readily obtainable. Application of microprocessors permitted avoiding multiple connectors and setting the mode of operation of an echo sounder using a numerical control panel. It is possible to set a great number of various parameters, each of which may assume several values.

Color indicators are utilized widely owing to a high clearness of the color representation of commercial concentrations and the ease of distinguishing color indications. It is known that an eye can distinguish approximately two times more gradations of a color than of brightness. As a result, there is the possibility of using up to 16 colors, each of which corresponds to a determined level of echo signals. A color indication increases the contrast, the ability to distinguish targets, and the precision of estimating the differences of concentration density. This makes it possible to differentiate signals from individual fish against a background of sound-scattering layers and, near the bottom, to pinpoint denser parts of commercial concentrations, and to estimate their density.

It should, however, be noted that the application of color electronic indicators does not exclude the use of recorders. Color recorders (printers) are used in the complete treatment of echo signals in stationary conditions for constructing plane tables of distribution of commercial concentrations, graphs, typical echograms, and so on. In some cases, it is expedient to use printers in marine conditions. They can be applied, for example, in carrying out long-term search works or passing observations (see Chapter 9), when it is important to compare current echograms with those already observed on a monitor, for the analysis of a situation.

As mentioned in the previous chapter, the possibilities of search and aimed fishing of commercial concentrations are determined by the degree of investigation of a region and the character of the distribution of concentrations. Practice shows that in the exploited regions, where a large fishing fleet operates, a local search of commercial concentrations can be ensured by use of an echo sounder. Generalization of the results of the search and catches by radio transmission between fisheries vessels usually allows reception of a clear enough presentation regarding the distribution of concentrations in a region. In such cases, an echo sounder is used for specifying the location of commercial items in the area of fishing.

An echo sounder also permits one to follow the depth location of a concentration, which is important for establishing the horizon of fishing by a variable depth trawl, drift nets, and other fishing gears. For bottom trawl operations, an echo sounder makes it possible to choose locations where fish hug the bottom; it marks the unevenness of the bottom.

Unfortunately, an echo sounder has limited possibilities in aimed fishing. It records signals outside of the boundaries of the vessel because of the width of its beam; i.e., for several dozens of meters in the best case. Therefore, fish schools and shoals can be detected only if a vessel passes over them, and, for fishing a detected shoal, it is necessary to repeatedly meet with it.

It is natural that in aimed fishing, meeting with a shoal by using the readings of an echo sounder can be rather approximate. As to small schools, it is only possible to meet them by chance with the help of an echo sounder. Therefore, in fishing small schools by a trawl, an echo sounder is only useful in contouring the relief of a trawled part of the bottom and in sensing the presence of fish under the bottom of the vessel. Reliable results of aimed fishing of detected commercial concentrations by the readings of an echo sounder are possible only in the case when concentrations have a large horizontal extension.

As stated in the previous chapters, echo sounders allow for a search of commercial concentrations at great depths, even registering individual targets. At the same time, even the most up-to-date echo sounders do not always correctly reflect the real distribution of items by depth. This is especially true in relation to item registration near the bottom and at the surface of the sea.

It is difficult to carry out a search for commercial concentrations, which hug the water surface. Because of the surface reverberation, as well as a vessel frightening off fisheries items located close to the surface, a search for them is often possible only beginning from a depth of 5–10 m or more below the keel of a vessel. For detecting fish in the upper layers of the water, different types of sonar are used. It is possible to detect fish concentrations near the surface with the help of towed transducers operating upside down. Preliminary experimental works have provided hopeful results.

Practice shows that echo sounders do not always register dispersed fish at the bottom and, in the case when they do register, recordings do not often correspond to catches: it is possible that an echo sounder shows only a few fish but catches are significant; and, on the contrary, it can appear that, according to recordings, there is a great amount of fish but the catch is light. The discrepancy between recordings of fish and their real distribution is explained by the masking of bottom fish recordings by reflections from the ground.*

One of the reasons for the masking of recordings of bottom fish on the indicator of a fish-finding instrument is the sphericity of the front of sound waves. As seen from Figure 4.1, top, echo distances down to bottom fish, which fall at the sides of an ultrasonic beam, exceed the real depth because of the wave front sphericity; therefore, they are undetected by the instrument. An echo sounder can detect only fish falling into the segment indicated in black in Figure 4.1, top.

Assuming the section of the sound beam as round and the bottom as absolutely even, we will determine the diameter of the detection zone D, within which bottom fish are registered over the line of the bottom. Simple calculations show that

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* The reasons for masking of commercial concentration near the bottom were first investigated by Yudanov.[1]

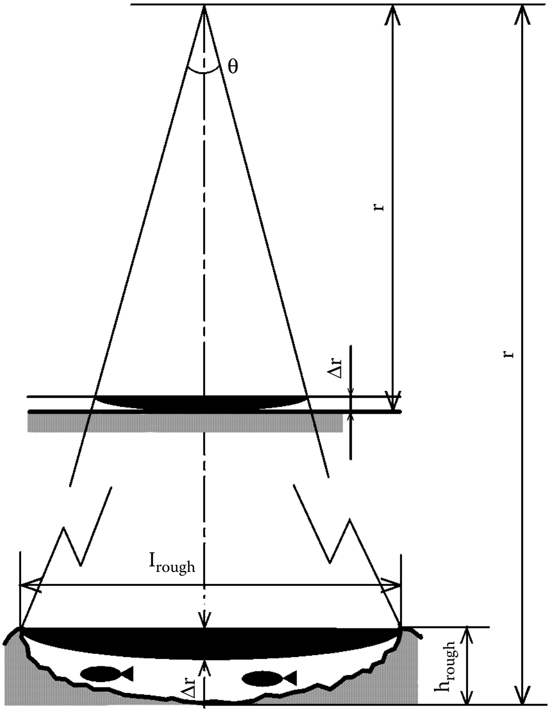

FIGURE 4.1 Scheme of masking recordings of fish near the bottom because of spherical wave front (top) and unevenness of the ground (bottom).

$$D = \sqrt{8r\Delta r} \tag{4.1}$$

where Δr is the thickness of the bottom layer within which the fish keep and r is the depth of the place.

The effective width of the sound beam of an echo sounder is determined from the relation

$$\theta_{eff} = 2\arccos \frac{r}{r + \Delta r} \tag{4.2}$$

As follows from formulas (4.1) and (4.2), the effective width of detecting bottom fish by an echo sounder is determined only by the depth of the place and the fish location relative to the bottom; it does not depend on the width of the characteristic directivity of a transducer. It is also typical that, in registering bottom fish, actually only a very narrow part of the sound beam is used and the diameter of the zone has rather limited dimensions.

Using formulas (4.1) or (4.2), we obtain the following widths of a detection zone with regard to a fish located at a depth of 200 m: if the distance between a fish and the bottom is equal to 0.1 m, the width is 12.6 m; if the distance is equal to 0.5 m, the width is 28.3 m. In the first case, the corresponding area of the detection zone is 125 m^2; in the second one, 629 m^2. Typically, an area of the zone of detecting an individual fish at the indicated depth of the water thickness by a wide beam echo sounder is on the order of a dozen thousand square meters. By comparison of these data, it is seen that, in detecting bottom fish, only a small part of the ultrasonic beam is actually used. The closer to the ground the fish are pressed, the greater part of the energy insonified by an instrument is lost to no purpose. It is obvious that to better utilize the insonified energy of a sound beam, it is necessary to apply narrow-beam transducers during the search for bottom fish.

To have an idea of the extent of masking of the recordings of bottom fish because of sphericity of the sound wave front, let us consider how strongly the volume of the segment of the detection zone within the bottom layer (V) can differ from the volume of a cylindrical zone of the same thickness but in a pelagic area (V_{pel}):

$$K = \frac{V_{pel}}{V} = \frac{D_{pel}^{\;2}}{4r\Delta r} \tag{4.3}$$

where D_{pel} is the diameter of the zone of detecting fish by echo sounder in a pelagic area, which is determined from the characteristic of the range.

The mentioned coefficient K characterizes the extent of decrease of the zone of detecting bottom fish as compared to the zone in the pelagic area because of the sphericity of the wave front. The decrease of the detection zone is especially great in cases when fish keep very close to the bottom. If there are two identical fish concentrations within the water column and near the bottom, an echo sounder will register pelagic fish in much greater quantity than those keeping near the bottom (the difference will be equal to K times). For instance, with $r = 100$ m, $D_{pel} = 60$ m and $\Delta r = 0.5$ m, the zone of detecting fish near the bottom decreases $K = 18$ times. The minimal difference in the volumes of detection zones is with $D = D_{pel}$; then the coefficient $K = 2.0$.

Another cause for masking of the readings of bottom fish is unevenness of the ground. As seen from Figure 4.1, bottom, echo distances from the transducer of an echo sounder to the high points of a rough bottom are usually shorter than to the bottom fish.* A fish-finding echo sounder insonifies a great enough area of the bottom that recordings of bottom fish can be masked by the unevenness located not only under a vessel but also rather far from it (the width of a bottom detecting zone is much greater than one for fish).

It follows from the figure that the complete masking of bottom fish occurs if the unevenness h_{rough} is larger than the height of the segment of the spherical wave front; i.e., when

$$l_{rough}/r < \theta_{bottom} \tag{4.4}$$

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[*] The mentioned phenomenon takes place with a dispersed distribution of fish only. When fish keep near the bottom in a dense layer, there is a partial masking of fish, which can be registered under the corresponding scale of indicator.

$$l_{rough}{}^2/r < 8h_{rough} \qquad (4.5)$$

where l_{rough} is the distance between the unevenness, m; and θ_{bottom} is the effective width of the beam of an echo sounder in registering the bottom, rad.

Conditions (4.4) and (4.5) shows that the masking action of the bottom occurs more strongly in cases of larger unevenness of the relief and greater depth. Not only the height of unevenness is important, but also the distance between the peaks. Thus, bottom fish, located between two peaks, will be masked more strongly if the height of unevenness is large and the distance between them small.

Areas of the bottom insonified by an echo sounder can be rather significant, especially with great values of the width of detection zone and large depths. For example, the area of the bottom insonified by an echo sounder at depths on the order of 100 m make up thousands, and at 500 m, dozens of thousands, of square meters. With such significant areas of insonification of the bottom, the probability of meeting with unevenness of the ground is great; consequently, there is a high probability of masking of bottom fish.

The impact of unevenness of the ground on the masking of bottom fish is particularly significant over stony parts of the bottom. The point is that trawl fishery is carried out over parts of the bottom that are difficult to access, as a great amount of fish often accumulate exactly over such ground. The search for bottom fish becomes especially difficult in this case.

As previously mentioned, the degree of fish masking depends on the height, the extension, and the configuration of unevenness, as well as on the distance between fish and the bottom. Naturally, in each specific case, it is impossible to take into account the entire complex of factors affecting the masking of bottom fish. In order to take into account the extent of masking of recordings of bottom fish by the unevenness of the bottom, it is necessary to know the characteristics of the relief in the region under investigation; namely, the average values of height and distances between peaks of roughness. It is possible to obtain such information on the relief with the use of a measuring echo sounder with transducer possessing a very narrow characteristic of directivity.

Especially great masking of recordings is possible at depth overfalls. This is because of the difference of zones of detecting the bottom and fish by echo sounder. The zone of detecting the bottom is much greater than that for fish. Therefore, with an abrupt slope, echo signals from the areas of the bottom, which are insonified by the extreme rays of the ultrasonic beam, can arrive first at the transducer of an echo sounder, and afterwards from fish located within a narrower zone. Such a phenomenon, when the recording of a bottom fish is marked beneath the bottom elevation, takes place with certain angles of inclination of the bottom. The value of the limiting angle of the bottom inclination β_{lim}, with which such a masking of bottom fish is possible, is determined by the geometry (Figure 4.2) and is calculated as:

$$tg\beta_{lim} = (\cos\theta_1 - \cos\theta_2)/(\sin\theta_2 - \sin\theta_1) \qquad (4.6)$$

where θ_1 is the effective width for fish located at a determined depth and θ_2 is the effective width for the bottom at the same depth.

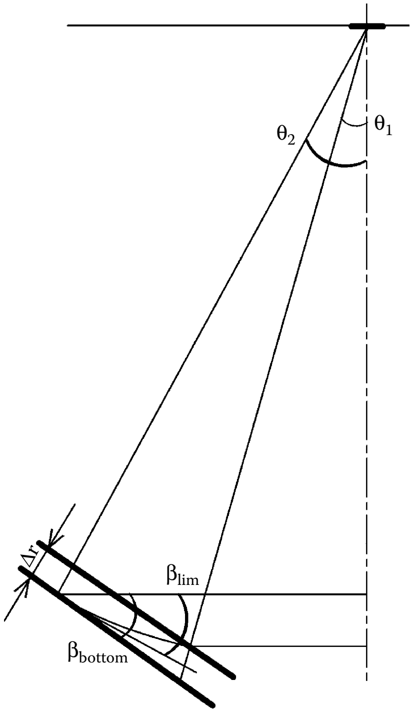

FIGURE 4.2 Scheme of masking the fish recordings by abrupt depth overfalls (the layer Δr between the two parallel planes is masked).

Substituting into formula (4.6) the values of the width of the sounder beam, one can determine the limiting values of the angles of inclination of the beam with which the masking of recordings of bottom fish is possible. Naturally, the values of beam width, calculated regarding rather dense fish concentrations, will be greater than those for dispersed aggregations. This means that, in the case of the presence of dispersed fish aggregations, their masking by depth overfalls is displayed more strongly than for dense concentrations.

To more clearly imagine dependence of the degree of masking of bottom fish on the inclination of the bottom, let us determine the thickness of the bottom layer Δr, in which complete fish masking takes place. It follows from Figure 4.2 that

$$\Delta r = r(\cos\theta_1 - \cos\theta_2)(\sin\beta_{\text{bottom}} - \sin\beta_{\text{lim}})/\sin\beta_{\text{lim}} \tag{4.7}$$

where β_{bottom} is the real angle of inclination of the bottom.

It is seen from relation (4.7) that the thickness of the masking layer (i.e., the extent of masking effect) grows with increasing depth r and with the steepness of an overfall β_{bottom}. Therefore, the partial or complete masking of bottom fish recordings is possible, first of all, at overfall of great depths. In the presence of significant unevenness at overfalls, the degree of masking is still higher.

Using formulas (4.6) and (4.7), let us estimate the values of the beam width and the bottom layer thickness Δr, with which masking of bottom fish is possible. Experimental results show that regarding a wide-beam echo sounder, the effective angle in detecting a stony bottom (θ_2) can be nearly twice as large as that for a fish concentration (θ_1). Thus, if for example, the depth $r = 500$ m and $\theta_1 = 22°$, then $\theta_2 = 36°$. It follows from relation (4.6) that $\beta_{lim} = 29°$. With the steepness of the overfall $\beta_{bottom} = 40°$, the thickness of the masking bottom layer, as determined from formula (4.7), $\Delta r = 23$ m. With $\beta_{bottom} = 60°$, $\Delta r = 63$ m.

Of course, such a strong fish masking at overfalls can only occur with a great steepness of overfall and with the wide acoustic beam of an echo sounder. The difference in the zones of detecting fish and the bottom with a narrower transducer beam is not great; therefore, the masking effect is much less pronounced.

A radical means, with the help of which it is possible to avoid the masking of recordings of bottom fish by an uneven bottom, is the application of echo sounders with narrow-beam transducers. Using a narrow beam in an echo sounder allows for insonifying the water space only directly under a vessel. Then echo distances to obstacles will correspond to the true depths of their location; therefore, the echogram will represent the real distribution of bottom fish and of unevenness of the ground. For detecting bottom commercial items not only directly under the vessel but also slightly aside, it is expedient to apply the equipment with narrow-beam scanning in the transversal plane.

4.2 PECULIARITIES OF DETECTION OF COMMERCIAL ITEMS

The character of images of individual items and their concentrations on the echograms of acoustic instruments is determined, to a great extent, by the parameters of the devices themselves. In particular, the sensitivity of instruments, the duration of transmissions, the directivity of a transducer, and the scale of registration have a great impact on the intensity of echo signals and the shape and dimensions of recordings of commercial concentrations and the bottom relief. As the dimensions and structure of concentrations are usually determined by the readings of acoustic instruments operating vertically, let us consider the peculiarities of a registration of various concentrations and of the bottom on the echograms with regard to fish-finding echo sounders.

The results of our investigations show that the main reasons for distortions in recordings of acoustic instruments, which should be obligatorily taken into account in interpreting echograms, are the nonuniform scale of registration in recorders, the breadth of the characteristics of directivity of a transducer, and additional reflections inside the concentration, from the water surface and from the bottom.

DISTORTIONS FROM A NONUNIFORM SCALE OF REGISTRATION

The vertical scale of the indicator of an echo sounder depends upon the speed of the vertical scanning of a display or upon the motion of the registering pen of a recorder, which is set precisely enough with regard to a specific range of depths.

Therefore, it is possible to consider the vertical scale of each range of an echo sounder as practically constant.

The horizontal scale of recordings is determined by the speed of the vessel and the speed of horizontal scanning of a display or the paper speed. Therefore, unlike the vertical scale, it can vary within great limits at each range.

In most cases, the horizontal scale of recordings on indicators is much smaller than the vertical one. As a result, the images on the echogram of fish concentrations and the bottom are always strongly narrowed. Variations of the speeds of horizontal scanning of a display or of the paper speed and of vessel motion disturb the proportions of images of schools and the bottom relief. At full speed, small schools are registered as narrow touches, and a declivity as an abrupt slope. At slow speed, recordings of schools are registered wider, and a slope, slightly more gently.

In recording concentrations and the bottom relief with an echo sounder, distortions from the nonuniform scale of registration should be always taken into consideration in acoustic reconnaissance.

DISTORTIONS CAUSED BY THE TRANSDUCER DIRECTIVITY CHARACTERISTIC

A fish-finding echo sounder registers commercial concentrations distortedly; records of schools and concentrations differ in shape from real ones. Let us consider the variation in the envelope of echo signals at different steps of spreading of acoustic waves on an example of registration of a concentration with an EK60 Scientific Sounder System (Figure 4.3). It is seen on the graph how strongly the U(r) value can change depending on the distance from a transducer to the impulse volume. The echo signal envelope also depends on concentration density, individual fish acoustic section, and a number of parameters of the fish-finding instrument.

The retarded rise and fall of the echo signal envelope leads to the registration of echo signals on the echogram with a certain shift in time and the length of traces is apparently different from the real concentration size in the detecting direction.[2,3] To account for distortions in recording, it is necessary to know the detection zone of the acoustic instrument for the fish concentration under survey, as well as the value of the dead zone at detecting its upper border (see Section 2.2).

It is possible to determine the value of distortions in recordings with the help of simple trigonometric relations. Thus, the increase in the horizontal extension of schools (Δ_L) can be found from the following relation:

$$\Delta_L = 2r\mathrm{tg}\,\frac{\theta_{\mathrm{eff}}}{2} \qquad (4.8)$$

It follows from Figure 4.3 that the values of distortions of the depths of the upper and lower borders of concentrations are correspondingly equal to:

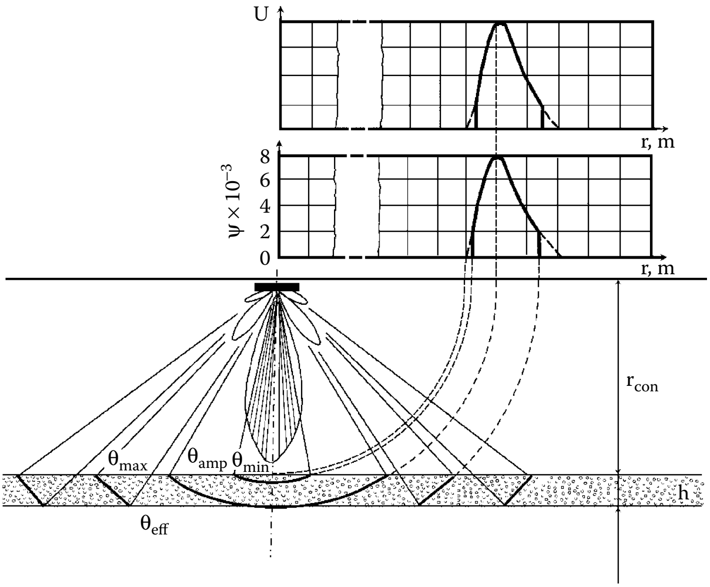

FIGURE 4.3 Scheme for calculating a zone of detecting a fish concentration, as well as charts of changing the integral directivity factor and the echo signal envelope regarding the registration of multiple targets by an EK60 Scientific Sounder System.

$$\Delta r = r_{cen} - r_{con} = r_{con}\left(\sec\frac{\theta_{min}}{2} - 1\right) \tag{4.9}$$

$$\Delta r = r_{per} - (r_{con} + h) = (r_{con} + h)\left(\sec\frac{\theta_{eff}}{2} - 1\right) \tag{4.10}$$

It follows from relations (4.8), (4.9), and (4.10) that, in order to determine the errors in recordings of schools and concentrations, it is necessary to know the depth of their location r, the effective width of the acoustic beam θ_{eff}, and the minimal directivity angle θ_{min}. The depth of location is found directly from the echogram, and the effective angles from the polar range characteristics of detecting a concentration and the angular diagram of the dead zone at detecting its upper border.

Let us show the course and results of calculation of distortions on an example of registration of a fish concentration by an EK60 Scientific Sounder System. Having determined the effective width of the sound beam from the diagram of the detection zone (Figure 2.5), and the minimal directivity angle from the angular characteristic of the dead zone (Figure 2.7), we calculated from formula (4.9) and (4.10) the distortions in recordings of fish concentrations at different distances.[3] The results of calculating the distortions of recording the thickness of the concentration are given as graphs in Figure 4.4.

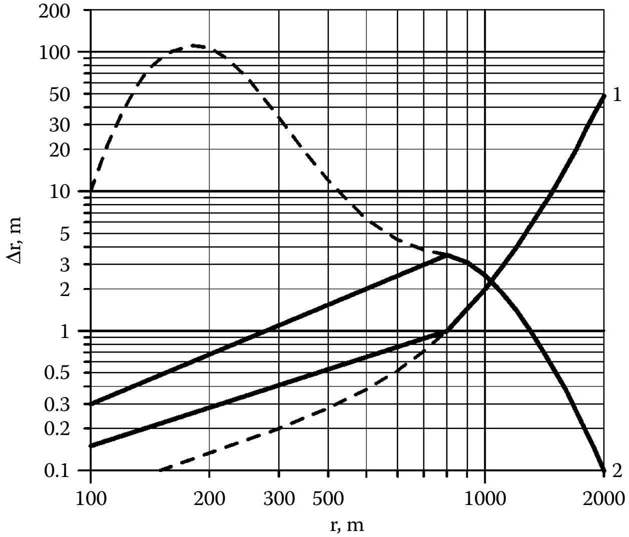

FIGURE 4.4 Distortions in registering the border of fish concentrations (σ = 10 cm^2, ρ_v = 0.1 sp/m^3, h = 50 m) by an EK60 Scientific Sounder System operating at 38 kHz depending on the distance: 1, the upper border; 2, the lower border. The dashed line shows the distortions without the TVG.

As seen in the figure, without the TVG, the distortions in recording the lower border of the concentration are great at short distances and are accounted for by detecting the concentration with the side lobes of the transducer directivity diagram. The application of the TVG considerably diminishes these distortions. The distortions of recording the upper border of the concentration are considerable only if the target is located close to the maximum range of detection.

The above method of calculating distortions in recorded concentrations makes it possible to determine the real vertical dimensions of dense fish aggregations.

The beam width distorts not only recordings of concentrations but also of the bottom relief. As the line of the bottom is received from the marks of minimal echo distances — from the maximally elevated points of the bottom — all the other insonified parts of the bottom, independent of whether they are under or abeam a vessel, are recorded below the line of the bottom and cannot affect the shape of this line. As a result, so-called dead zones are formed, within which it is impossible to determine the relief of the bottom.

It is possible to decrease distortions of recording of commercial items and of the bottom only through the use of narrow-beam transducers. However, with a narrow beam, the tossing of a vessel has a stronger impact on the operation of an echo sounder and the conditions for registering dispersed fish are worse. To ensure the ability of an echo sounder to solve the tasks of the search and interpretation of recordings, it is necessary to use in one instrument wide- and narrow-beam transducers.* This configuration renders an echo sounder more convenient for search work. During a search for fish, the wide-beam transducer is switched on, while the narrow-beam transducer is used to elucidate the degree of unevenness of the ground, to determine the actual dimensions of concentrations, their structure, and the position of schools relative to the vessel and their distribution by depth.

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* This requirement was first formulated by Yudanov.[1]

DISTORTIONS FROM ADDITIONAL REFLECTIONS

Echo signals can arrive at the transducer of an echo sounder in the normal way (transmitter-obstacle-receptor) as well as by a more complicated one. Moving away from an obstacle, echo signals may additionally reflect from the sea surface, then return to the obstacle, and so on. As a result, besides main reflections, an echo sounder will register so-called additional reflections from obstacles. Additional reflections can be received from fish schools and concentrations, from the bottom, and from other obstacles.

The conducted analysis of echograms shows that the real thickness of dense concentrations, located close to the surface, may differ greatly from that registered by a recorder. If the depth of location of a school or concentration exceeds its height, repeated reflections will be recorded under the main image (Figure 4.5, left). In contrast, if the depth of location of a concentration is equal to or less than the height, repeated reflections will be registered together with the main reflection (Figure 4.5, right). In this case, it is impossible to determine the border between the main and repeated images and distortions of the thickness can be great. It is necessary to orientate fishing gear on the upper part of the recordings; otherwise, the gear may pass beneath the fish and not provide a catch.

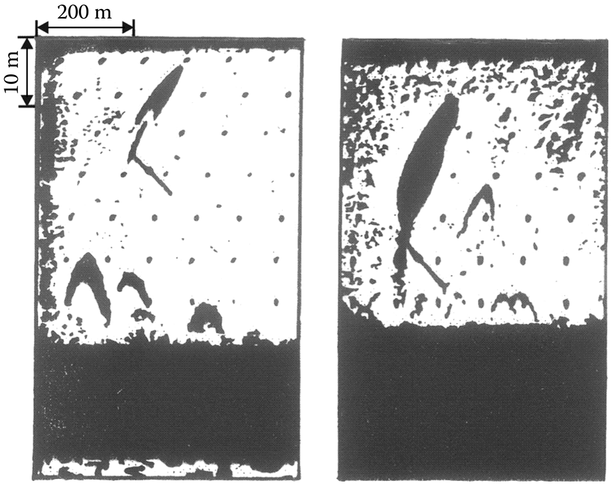

FIGURE 4.5 Recording of complementary reflections from schools (range, 60 m). Left: the depth of the school location is larger than its height; Right: the depth of the school location is smaller than its height.

Additional distortions in recordings of dense schools can occur as a result of multiple reflections within concentrations. Such distortions display especially strongly with registration of surface and bottom concentrations of a large number as reflections from individual fish in a concentration alternate with those from the water surface or sea bottom, lengthening the path of echo signals. Distortions of recordings of bottom schools and concentrations are sometimes so great that their lower borders are registered far below the line of the bottom (Figure 4.6).

Additional reflections from the bottom can contribute to distortions in recording. Reflections from the bottom arrive and register on the tape of a recorder not only during the first move of the pen, but also during the second and following ones. Being registered by a recorder as results of subsequent transmissions, additional reflections from the bottom darken the echogram and disturb the search. It is easy to interpret these records as fish concentrations (Figure 4.7).

The intensity of additional recordings from the bottom depends, first of all, on the general intensity of an echo sounder, on its detection range. In order not to allow false recordings to darken the working area of an echogram, two close ranges are used; when switching on another range, false recordings disappear or are registered at a different depth.

It should be noted that, in some cases, additional reflections from the bottom, for the first move of the pen, might be useful. Due to the greater scale of recordings and smaller intensity of echo signals, by recording repeated reflections from the bottom, it is easier to differentiate bottom schools from unevenness of the bottom. In this case, when an instrument registers schools, the recording for the second reflection from the bottom has a different shape. Initial reflections for the second and the following moves of the pen can be successfully used for receiving the large-scale recordings of commercial concentrations when carrying out a search at great depths.

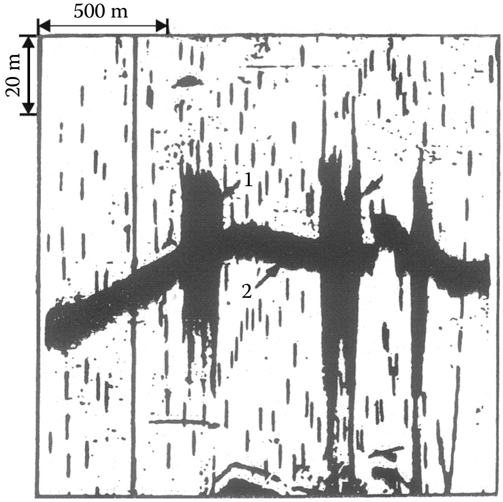

FIGURE 4.6 Recording of dense bottom schools (range, 300 m): 1, the schools; 2, the bottom.

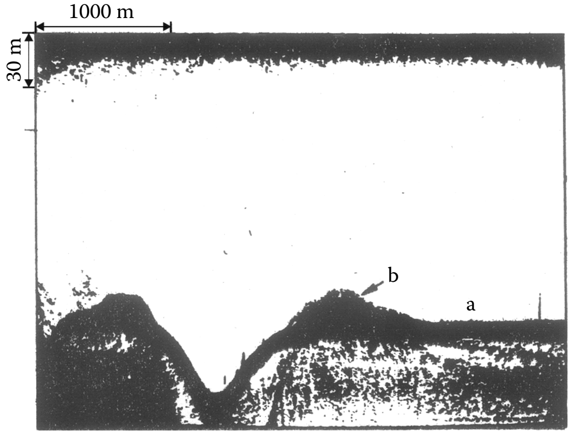

FIGURE 4.7 Recording of an uneven bottom by the echo sounder (range, 120 m): a, the main recording; b, recording of the repeated reflection from the unevenness of the bottom.

4.3 POSSIBILITIES OF DETECTION OF COMMERCIAL ITEMS BY SONAR

Acoustic instruments of horizontal location (sonar) are applied in investigating large expanses of the ocean. Having a great detection range, sonar allows investigating significant parts of the sea over a rather short time. Thus, with an average detection range of sonar equal to 1500 m and a vessel speed of 10 knots, it is possible to study a water area equal to 55.5 km^2. Under the same conditions, an echo sounder with a diameter of detection zone of 30 m allows for studying an area of 0.55 km^2. Thus, it is possible to investigate an area with sonar, in the same time, which is of two orders as large as that studied with an echo sounder.

Sonar enables one to detect concentrations far from the vessel, to receive a panoramic image of the distribution of commercial concentrations; to determine their extension, distance and bearing; and to carry out aimed fishing. Ensuring a permanent contact and the ability to follow detected schools, scanning sonar has proved itself to be an especially useful tool in fisheries of such fast-swimming fish as tuna, scomber, horse mackerel, and so on.

Sonar, in which the beam can be scanned with various inclinations of directivity within the hemisphere, is of significant interest. Scanning sonar permits carrying out an independent search in the vertical and horizontal planes; it ensures a simultaneous view on a color display, within the sector of 180° in front of a vessel (on the upper part of the screen) and transversal vertical scanning (on the lower part of the screen). A simultaneous investigation in the horizontal and vertical planes allows for fixing the distribution of commercial items by the area and depth, which is especially important for the search and for aimed fishing. Such a mode of operation of scanning sonar can be also used for quantitative estimation of commercial concentration (see Section 6.4).

An indicator of the underwater situation is widely used in modern scanning sonar. Computer treatment of acoustic information allows the distance and direction to a target, its depth, and the speed and course of a vessel to be displayed in digital and graphic form on the color screen of such an indicator; the plane table of the distribution of concentrations relative to a vessel and to fishing gear, the direction, and speed of movement of commercial items and other information are reflected as well. Thus, practically all information required for the estimation of fishing conditions during aimed fishing can be displayed on the screen of an indicator. This makes it possible to operatively control the process of fishing the concentrations, leading to a substantial increase in the efficiency of fisheries.

Sonar is most effectively used for aimed fishing of local commercial concentrations, especially for large schools. Precise location of rare commercial schools plays the determinant role in fishing them.

Experience in the use of sonar shows that it is important that a concentration selected for fishing would be under constant monitoring by acoustic instruments up to the moment of its capture by fishing gear. Permanent acoustic contact with the fish is especially required in aimed trawling and fishing by purse seine. A gradual change of the angle of inclination of the ultrasonic beam of a sonar allows a vessel to follow fish up to the minimal distances, permits the operators not to lose fish when approaching them, and provides a more exact depth when locating schools and concentrations.

It is much more difficult to maintain the acoustic contact when a concentration is behind a vessel. The detection of fish is often limited by the disturbances of the wake current, and the contact with them may be lost. Fish following within the stern sector is only possible when the sonar beam is inclined at certain angles, when the wake current does not mask the readings of fish. More reliable contact with fish can be ensured with the help of special sonar, which is fixed on the trawl itself. Such sonar allows for detecting fish with a scanning beam within the wide sector before the trawl and fixing its location on a display relative to the trawl.

In order to precisely aim a fishing gear at detected fish, it is necessary to know their depth of location. We usually know the approximate distribution of fish by depth in a fisheries area; however, often, within the same region, separate schools and concentrations are situated at different depths. Therefore, when operating a trawl at various depths, it is necessary to know, prior to arrival of the vessel at a concentration, the depth at which fish are concentrating so that in the process of trawling one may change the horizon of the trawl motion.

For the case of a complete homogeneity of the temperature structure, the depth of located fish can be easily determined by the angle of inclination of the ultrasonic beam of sonar and the detection range. However, in the presence of gradients of the speed of sound because of temperature gradients, refraction of the beam occurs and its path will be curvilinear. As a result, in determining the depth of located fish, significant mistakes can be made. These mistakes are usually accounted for by the method of calculation.

An error in the depth of located fish can be also because of the directivity characteristic of a sonar transducer. The angle of inclination of the lowest ray may be significant with a wide enough sector of insonification; the angle of inclination of the lowest ray cannot be determined precisely as it depends, to a great extent, upon the sensitivity of the instrument and the reflectivity of registered concentrations.

Thus, even in the case where there are data on the vertical refraction of the sound beam, it is impossible to precisely determine the depth of located fish by sonar readings. Therefore, one must usually be satisfied with the approximate determination of depth of located fish concentrations as the distance at which the sonar loses contact with the fish. A minimal detection zone, at which the contact with fish is lost, depends on the physical conditions of the sea and the angle of inclination of the beam, and is determined by experimentation for each commercial region. It is natural that with such an approximate determination of the depth of located fish, it is possible to only roughly establish the horizon of movement of a trawl. Precise correction of the trawl movement is made after determining the depth of located fish by echo sounder, as well as with the help of a trawl sonde.

With great nonuniformity of temperature structure with depth, the sonar beam has an abrupt path and the conditions for detecting fish become so unfavorable that it is difficult to detect dense schools within the water column even from distances of 400–500 m. In shallow seas, the range of detecting fish with sonar also decreases because of the strong bottom reverberation. In these cases, the bend of the ultrasonic beam towards the ground only strengthens the bottom reverberation. For this reason, search by sonar at small depths does not often produce substantial results.

The detection of bottom fish by sonar is especially difficult. This is explained by the fact that the zone of detecting the bottom is, as a rule, significantly greater than that for fish. Therefore, if fish are located directly over the bottom, the sonar first registers echo signals from the ground and then from fish (Figure 4.8). It is impossible to separate readings of fish from reflections of the ground in these cases.

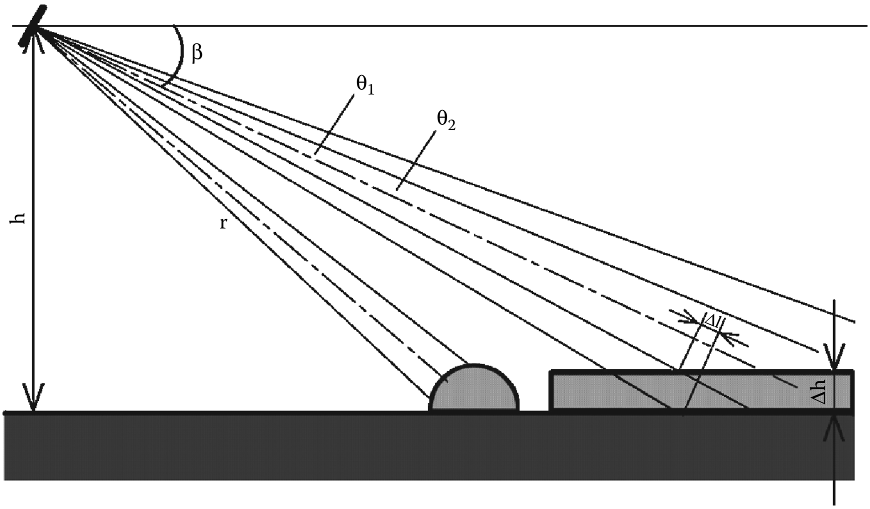

FIGURE 4.8 Scheme of registering bottom fish concentration and schools by sonar.

To simplify the following reasoning and calculations connected to the analysis of the possibility of detecting bottom concentrations by sonar, let us consider the path of the sonar beam as rectilinear. The geometry of Figure 4.8 shows that the following relation should be accomplished in order to detect fish or other commercial items near the bottom:

$$\Delta h > h\left[1 - \frac{\sin(\beta + \theta_2/2)}{\sin(\beta + \theta_1/2)}\right] \tag{4.11}$$

where h is the depth of the location; Δh is the thickness of the bottom layer, within which fish congregate; β is the angle of inclination of the transducer beam relative to the horizon; and θ_1 and θ_2 are the effective width of the ultrasonic beam of sonar for fish and the bottom with the given detection range.

Using this formula, it is possible to establish under what conditions bottom fish may be detected by sonar. If, for example, h = 100 m, β = 25°, θ_1 = 20°, θ_2 = 10°, then a concentration can be detected with $\Delta h > 22$ m. Thus, the delay of echo signals from bottom fish, and then the masking of their readings, stops occurring only when a significant distance between the fish and the ground exists. In order to avoid masking of the readings of bottom fish, the sonar must have a narrow ultrasonic beam.

Sonar currently in use possess a rather wide acoustic beam; therefore, they are able to detect fish near the bottom, or against a background of signals from the ground, only when useful signals from fish prevail over those from the bottom. Such cases can take place in operating over fishing grounds possessing a weak reflectivity; for example, in registering fish near a bottom covered with silt. It is also possible to separate echo signals from bottom fish in the presence of even and flat ground when the sonar beam is reflected from the ground smoothly; i.e., mainly aside, nearly not returning backward.

In practice, the surface of the bottom is very rarely even and flat for a large distance. However, with bottom unevenness where the dimensions are small in comparison with the length of the acoustic wave, the reflection goes smoothly; i.e., as from an absolutely flat surface. To get an idea when the reflection will be smooth, let us use the criterion of Rayleigh, which, regarding our task, can be written in the following form[4]:

$$\sin\beta < \lambda/(6\Delta) \tag{4.12}$$

where Δ is the height of the unevenness of the bottom.

Using this relation, it is possible to determine the conditions of a smoothed reflection from the bottom. For example, if the height of unevenness Δ = 20 cm, it follows from relation (4.12) that a smoothed reflection from the bottom appears with the angle of inclination of the sonar beam at an operation frequency of 20 kHz (λ = 7.5 cm) no more than $\beta < 3.5°$, and with Δ = 3.0 cm, $\beta < 25°$.

Thus, the requirements relative to the unevenness of the bottom in order to receive a smoothed reflection are very high. With increased operation frequency and a transducer inclination angle, these requirements are still higher.

Let us determine detection ranges, which are required for sonar to ensure the smoothed reflection from a comparatively even bottom. From the geometry of Figure 4.8 and relation (4.12) we obtain:

$$r = 6\Delta h/\lambda \tag{4.13}$$

where r is the inclined distance to the bottom.

It follows from formula (4.13) that a smoothed reflection from a comparatively even bottom at great depths is possible only with distances r significantly exceeding the limiting detection ranges of modern sonar (Table 2.1). For example, with a depth of $h = 300$ m and a height of unevenness of $\Delta = 20$ cm, the inclined distance to the bottom is equal to $r = 4800$ m. Therefore, the impact of smoothed reflections from a comparatively even bottom can be observed, practically, only with the search for fish by sonar at shallow depths.

It has been experimentally established that, when operating sonar over even ground, the bottom reverberation is insignificant when the beam is incident upon the bottom at an angle smaller than 20°. This critical angle depends on the operation frequency and the ground composition. A bottom of gravel causes more troubles than sand or clay. It is difficult, or even impossible, to differentiate echo signals from fish near the bottom from those reflections from groups of stones on the bottom.

Besides with a smoothed reflection, diffuse scattering appears with an uneven surface of the ground, and the reflection from the bottom has a complicated characteristic of directivity, so-called spectral beams. The direction and amplitude of spectral beams depend on the extent of unevenness and the direction and length of the incident sound wave. If the unevenness is not very large, the directivity of signals reflected from the bottom reaches a maximum, corresponding to a geometric reflection. That is, a gentle incidence of the beam also leads to a smaller back reflection from uneven ground. Taking this into consideration, it is necessary to create conditions so that the sonar beam will meet the ground at a minimal angle. In particular, it is necessary to carry out the search for fish on gentle grounds in the direction of increasing depth.

4.4 PRACTICAL ESTIMATION OF SCOUTING POSSIBILITIES OF ACOUSTIC INSTRUMENTS

For the effective use of acoustic technique in fisheries, it is important to know the possibilities for search and for estimating the stocks of commercial items of various types of sonar and echo sounders. Investigating the possibilities of fish finding instruments is also required in order to elucidate the shortcomings of the equipment as well as in influencing its development.

As mentioned in the second chapter, the main search characteristics of acoustic instruments can be calculated. It was shown in Section 2.1 that in order to check the efficiency of work of an acoustic instrument, it is enough to only determine the energetic potential.

Field experience shows that, because of poor quality control during assembly and an insufficient level of technical service, energetic potentials of acoustic instruments of commercial fleet vessels are often considerably lower than nominal values. The lower the energetic potential, the smaller the range of detecting items with given acoustic sections. The variation of the detection range with the decrease of the energetic potential of the instrument is shown in Figure 4.9. As follows from the graph, a decrease in the energetic potential of 10 dB leads to a reduction in detection range of the instrument of about 55%.

Calculated values of the energetic potential may differ slightly from real ones, as rough estimates of the sound attenuation in water are used. In determining the energetic potential, it is necessary to account for excessive sound attenuation in the aerated sea surface layer, introducing a corresponding correction into formula (2.3).[5] Tentative values of excessive attenuation are found by comparison of the average value of the energy of bottom echo signals, obtained under different weather conditions and various speeds of a vessel, with echo signals from the same area of a smooth, desirably sandy, bottom in calm weather with the vessel stopped. The most reliable values of the coefficient of excessive attenuation can be found by using the special equipment.[6–8]

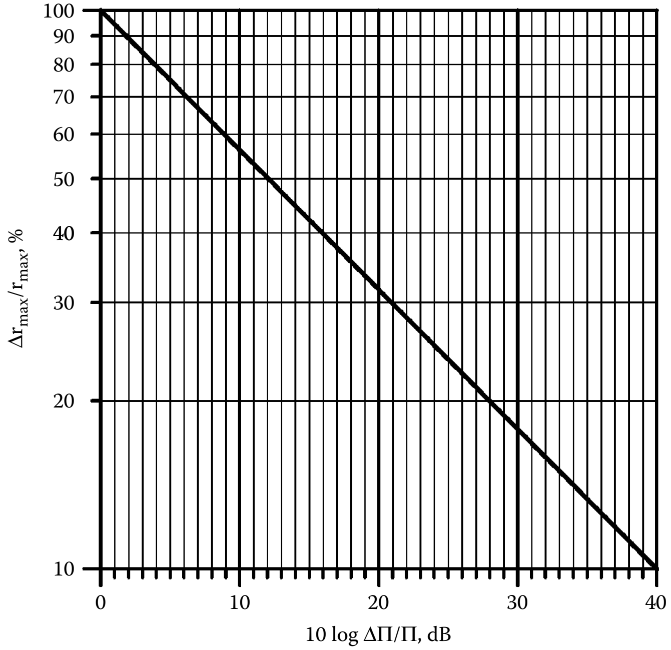

FIGURE 4.9 The change in the detection range with decreasing energetic potential of the acoustic instrument.

Measurement of the energetic potential should be carried out with different speeds of vessel motion and under a range of wave heights. The energetic potential of instruments of the same type can vary depending on the type of a vessel, transducer location, and other reasons. Therefore, it is important to record the real values of energetic potential in a technical logbook for each fish-finding instrument.

It is possible to approximately calculate the detection range of an acoustic instrument, to estimate theoretical possibilities of detecting surface and bottom concentrations, which are determined not only by the resolving capacity of the equipment but also by the efficiency of the expander of the scale of registering concentrations, the device for breaking bottom signals, and the stabilizer of sonar transducers. It is possible to theoretically determine the still more approximate possibilities of following commercial concentrations. All this is indicative of the necessity for obligatory experimental testing of calculated values for search characteristics of acoustic instruments.

The experimental estimation of the detection range of acoustic instruments is carried out with the help of standard targets with a known acoustic section.* Metallic spheres are used as standard targets in testing echo sounders. Angular reflectors serve the same purpose for sonar. As a result of experimental estimations, the detection range of the instrument is calculated regarding an equivalent target (for echo sounders, $R_{eq} = 10$ cm or $\sigma_{eq} = 314$ cm^2; for sonar, $R_{eq} = 2.0$ m or $\sigma_{eq} = 12.56$ m^2). The calculation is carried out based on the following formula:

$$r_{max}10^{0.05\alpha(r_{max}-r_o)} = r_o(\sigma_{eq}/\sigma_o)^{1/4}(\mu_{max}/\mu)^{1/2} \tag{4.14}$$

where r_{max} and r_o are the ranges of detecting the equivalent and standard targets, σ_{eq} and σ_o are the acoustic section of the equivalent and standard targets, μ is the minimal gain required for detecting the standard target with σ_o, and μ_{max} is the maximal (admissible) gain for detecting individual targets.

The absolute values of μ and μ_{max} are not necessarily required for calculating the range r_{max}. It is enough to know the ratio of these values relative to each other at various positions of the gain regulator. Detection ranges, determined in such a way, are compared with those calculated by formula (2.3). If there is a discrepancy, its reasons are revealed and corresponding corrections are introduced.

It is expedient to carry out experimental testing of search characteristics of acoustic instruments over specially equipped marine proving grounds through corresponding measurements on artificial targets.** For equipping a proving ground, a marine area of approximately one square mile with a comparatively smooth bottom and depths no less than 40–50 m is required. It is convenient to have such a proving ground near the fleet base. It is also desirable that a depth overfall would be located near a proving ground; this makes it possible to carry out measurements at small depths as well as at large ones.

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* When beginning an experimental test of the search characteristics of an acoustic instrument, it is necessary to be sure of its reliable operation and to know its energetic potential.

** Marine proving grounds are not only necessary for investigating the search possibilities of fleet utilized acoustic instruments, but also for testing new models of equipment, as well as for training the natatorial and technical staff in equipment operating.

On a proving ground, individual artificial targets are placed in a certain order throughout the water column and near the bottom. Angular reflectors and hollow spheres are used as such targets. The latter are used for determining the efficiency of detecting bottom concentrations with instruments and for estimating the quality of transducer stabilization, as well as for verifying the correctness of calibration of acoustic survey equipment (see Section 6.2).

The possibility of following the target and the precision of a sonar bearing are estimated with angular reflectors. The possibilities of following movable objects can be verified by taking bearing on towed targets. The detection ranges and the resolution of echo sounders are estimated by registering individual targets.

All individual and standard targets must be calibrated; their acoustic sections must be determined. To ensure the precise meeting of a vessel with various targets, landmarks and ranges are set up on a proving ground.

Besides the above-mentioned, it is necessary to measure noises of commercial and scientific vessels on a proving ground. The receiving sensitivity of an acoustic instrument is greatly dependent on the noise level (formula 2.35). It should be taken into account that most pelagic fish are frightened by vessel noises; so, noises can have a substantial impact on the efficiency of the work of an acoustic instrument. As the technical condition of mechanisms deteriorates during field operations and their noise levels increase, periodic control is required, especially before and after repairing a vessel. At a proving ground, such a control should include measuring the noise level over a wide spectrum of frequencies at various vessel speeds.

To estimate the search possibilities of the equipment regarding real concentrations, it is necessary to experimentally measure their detection ranges in commercial regions. Working in a fisheries area, it is expedient to first make acoustic observations of detected concentrations, studying the structure of the item distribution within the water column and near the bottom, the peculiarities of forming and disintegrating concentrations, daily vertical migrations, the reactions to a vessel and to fishing gear, and so on. Controlled fishing is necessary to determine the species and length composition of concentrations.

In order to determine the maximal depths of habitation of commercial items, it is necessary to carry out deepwater trawling and acoustic observations under the most favorable working conditions (calm weather and a stopped vessel). Using a calibrated instrument, the volume backscattering is determined for concentrations located at various depths. As a result, the maximal detection ranges of equipment are found; their correspondence to the depths of habitation of items is clarified. It is important to reveal the optimal modes of operation of fish-finding instruments and a vessel taking into account the character of distribution of different items and weather conditions.

The stated suggestions only touch the surface of the entire range of questions that should be answered when carrying out tests of new models as well as currently used instruments on proving grounds. During this work, the methods of estimating the search possibilities of the acoustic equipment should be developed; the measuring technique should be improved.

REFERENCES

1. Yudanov, K.I., Ultrasonic beam of echo sounder and distortions in recording demersal fish, *Fisheries*, 12, 71, 1956 (in Russian).
2. Yudanov, K.I., Peculiarities of registration of fish concentrations by acoustic instruments, *Fisheries*, 1, 46, 1973 (in Russian).
3. Kalikhman, I.L., Tesler, W.D., and Yudanov, K.I., Methods of determining the density of fish concentrations, in Meeting on Hydroacoustical Methods for the Estimation of Marine Fish Populations, 25–29 June 1979, II: Contributed Papers, Discussions, and Comments, Suomala, J.B., Ed., The Charles Stark Draper Laboratory, Cambridge, MA, 1981, 533.
4. Yudanov, K.I., *Interpretation of Echograms of Hydroacoustic Fish-Finding Instruments*, Vilim, E., Trans., Keter Press, Jerusalem, 101, 1971.
5. Yudanov, K.I., Kalikhman, I.L., and Tesler, W.D., *Manual of Acoustic Surveys*, VNIRO, Moscow, 124, 1984 (in Russian).
6. Borisenko, E.S., Bondarenko, V.M., Stefanov, S.R., and Chistoserdov, Yu.P., The investigation of sound attenuation in the sub-surface layer of the ocean by the autocirculation method, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series "Fishery Acoustic Problems," Yudanov, K.I., Kalikhman, I.L., Shabalin, V.N., Eds., VNIRO, Moscow, 136, 1983 (in Russian).
7. Borisenko, E.S., Investigation of losses of the acoustic energy in water-fish medium, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series "Fishery Acoustic Problems," Yudanov, K.I., Kalikhman, I.L., Bondarenko, V.M., Eds., VNIRO, Moscow, 32, 1989 (in Russian).
8. Borisenko, E.S., Results of experimental measurements of the excessive sound attenuation in aerated layers of the ocean, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series "Fishery Acoustic Problems," Yudanov, K.I., Kalikhman, I.L., Bondarenko, V.M., Eds., VNIRO, Moscow, 40, 1989 (in Russian).

5 Species and Size Interpretation of Recordings of Commercial Items

Determining the species and length composition of concentrations by acoustic instrument readings is of great importance in fisheries, as well as in search and investigation work when studying the distribution and behavior of fish and other aquatic items, estimating the commercial significance of detected concentrations, controlling the state of the stocks, and so on. It is possible to determine the species and length composition of commercial concentrations on the basis of the character of their registration by fish-finding instruments. The other possibility consists of the use of an instrumental method, through the measurements of target strength of items or of the resonance of their swim bladder. For this purpose, especially elaborated equipment is applied.

5.1 SPECIES AND SIZE INTERPRETATION OF ECHOGRAMS

It is possible to observe sonar readings on a display screen. Based on the readings on the sonar display, one can make judgments as to the dimensions and distribution of schools; the direction and speed of movement of commercial items are determined from an indicator of underwater conditions. However, such information can give only an insufficient, indirect idea on the species composition of detected commercial concentrations.

An echo sounder possesses incomparably greater potential possibilities regarding interpretation of concentrations than does sonar. Recordings on the tape of a printer or on the screen of an electronic display of an echo sounder furnish a great amount of information on lengths, shape, and quantity of detected fish schools and concentrations and on the depth of their location. Work experience with fish-finding echo sounders shows that their ability to register fish and other marine organisms varies widely. It is obvious that the character of readings of echo sounders is determined, first of all, by the distribution of registered items. A record on the echogram depends upon the shape taken in the water column by a fish concentration.

As was mentioned in Section 3.1, each fish species has its own peculiarities of distribution and behavior and, in various moments of time, can be represented on the echogram differently. Sometimes, fish keep dispersedly over a large area, while at others, they gather in schools or concentrations. Fish distribution by depth also changes during a year: fish keep either to great depths or to the upper layers of the water. Regular, daily fish migrations occur side by side with seasonal changes. During daily vertical migrations, dispersed fish may concentrate into schools in parallel with moving upward; in contrast, it sometimes happens that concentrations disintegrate into small schools, which then disperse.

Taking into account the fact that each fish species has its own peculiarities of behavior, its yearly and daily distribution cycles, it becomes clear why the character of recordings of fish in internal waters, in seas, and in oceans is so diverse and variable. To this diversity should be added echo recordings from various marine organisms (plankton, jellyfish, and so on), which are also subject to seasonal and daily changes. It is natural that with such a great diversity and so complicated a picture of the distribution of aquatic organisms, the interpretation of recordings of fish-finding echo sounders offers some difficulties.

The problem of species interpretation of readings of acoustic instruments can be solved under the condition that the distribution of different fish species within a specific water body is sufficiently studied; the structure, dimensions, and shape of schools and concentrations at different times of the day and year should be known; the impact of the conditions of the environment on fish behavior should be clarified. The knowledge of the difference in character and density of the fish distribution, in their behavior, is one of the main factors facilitating the species interpretation of readings of acoustic instruments.

At the present time, numerous results of acoustic observations have been accumulated on fish distribution and movement in various water bodies, on fish vertical migrations, and on their reaction to light and to fishing gear. All this data allows, in many cases, a revelation of the peculiarities of fish registration by acoustic instruments and provides one with the possibility of interpreting their readings.

It is a simple matter to interpret echo recordings in the case when a fish species of interest keeps separated from others and the region and the depth of its distribution is known. For example, in the Baltic Sea, the regions where, during certain times, only herring and cod exist, have been studied completely enough. Fishermen are knowledgeable of such commercial regions in practically any body of water where fisheries have been conducted for a long time. The question of interpreting the readings in these regions simply no longer arises.

If different fish inhabit the same region, knowledge of peculiarities of the distribution of different fish species is required for interpreting the readings. Usually, each species keeps within a certain range of depths. The vertical distribution of organisms depends on temperature and illumination; it is rather variable for different species. Therefore, where several fish species inhabit a region simultaneously, their separate distribution by depth is often observed. For instance, in the Baltic Sea, the layered distribution of cod, herring, and sprat is often observed. The distribution can depend not only on species but also on sex, as well as on the differences in the physiological conditions of the fish. In Figure 5.1 we see an echogram of a multilayered fish distribution in one of the commercial regions of the Baltic Sea. The control fishing showed that herring were in the upper layer and, just near the bottom, mainly cod.

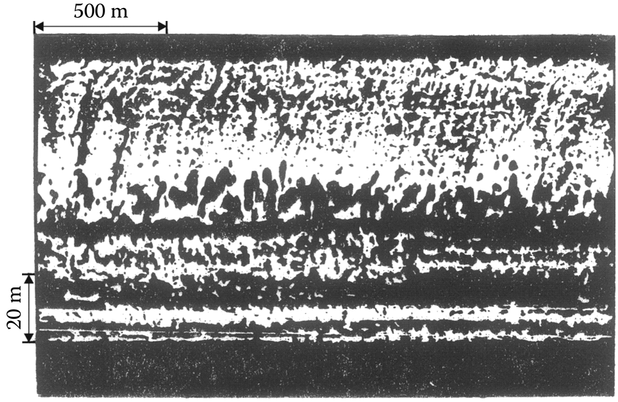

FIGURE 5.1 Recording of multiple layers of the fish distribution in the southern part of the Baltic Sea (range, 120 m).

Various forms of distribution and registration of different fish species facilitate the interpretation of their readings. For example, capelin and herring can keep to schools, while cod keep dispersedly; recordings of individual fish are often seen between echo recordings of cod concentrations. Recordings of individual specimens of cod can be distinguished with a schooled distribution (Figure 5.2). Even comparatively dense cod concentrations have a “friable” shape. The mentioned peculiarity of registering cod facilitates correctly differentiating them from recordings of small fish on the echogram. Concentrations of sea perch, hake, and other species of large fish are registered in a similar way. Unlike adult fish, concentrations of young fish are marked on the echogram by a continuous mass with clear enough borders. Concentrations of herring, horse mackerel, scomber, and other smaller fish are registered as dense monoliths.

In cases when various species of fish have approximately the same distribution, it is necessary to study their structure especially attentively in interpreting their recordings. It is required to take into account the impact of the main parameters of acoustic instruments on the character of recording. Thus, the shape and dimensions of recordings of individual fish and schools depend, to a great degree, on the directivity characteristic of the transducer, the working frequency, the sensitivity of the instrument, and the paper speed (see Section 2.4 and Section 3.1). On the other hand, parameters of individual fish, schools, and concentrations (their reflectivity, dimensions, distribution density) also have an influence on the character of echo recordings (see Section 1.4). This circumstance helps in interpreting recordings.

It is possible to determine the species of registered items by the dimensions, character, and clearness of recordings of individual fish with the invariable parameters of acoustic instruments. This is explained by the fact that reflections from large fish are stronger and their detection zones are wider than those from small ones. As a result, large fish are marked on the echogram more clearly and larger than small ones. Such a difference in readings permits distinguishing recordings of herring from those of cod, sprat, and other small fish. Thus, for example, in Figure 5.3, large,

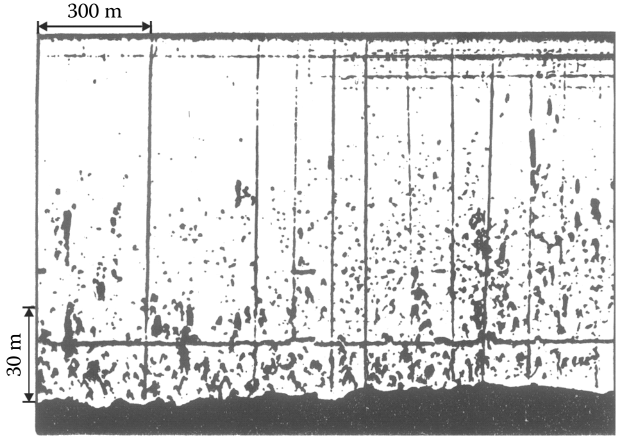

FIGURE 5.2 Recording of the cod concentration in the Barents Sea (range, 150 m).

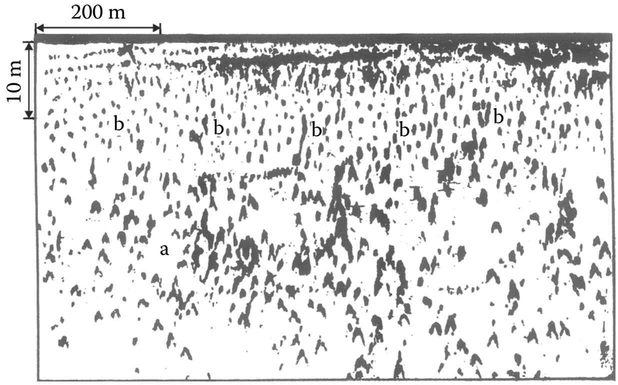

FIGURE 5.3 Recording of cod during their evening elevation (range, 60 m): a, individual specimen; b, young fish.

clear, upside-down check marks (a) are recordings of individual specimens of cod. It is possible to say, regarding the very small marks of similar shape in the same figure (b), that they are smaller than recordings of herring or sprat, and so, must be young cod fish.

Recordings of schools of various fish species have specific distinctions. Usually, acoustic instruments register schools as compact groups. As a rule, smaller fish form denser schools of a larger diameter than bigger ones. This circumstance confirms the fact that the dimension and density of a school depend on the length of items making up the school.[1] This regularity is clearly displayed in the character of registering schools of different species and may be applied to the species interpretation of recordings of acoustic instruments.

Let us consider, for example, a recording of cod in the Barents Sea (Figure 5.4). On the face of it, this recording appears to be of herring. However, with careful examination of the echograms, a substantial difference is revealed: recordings of

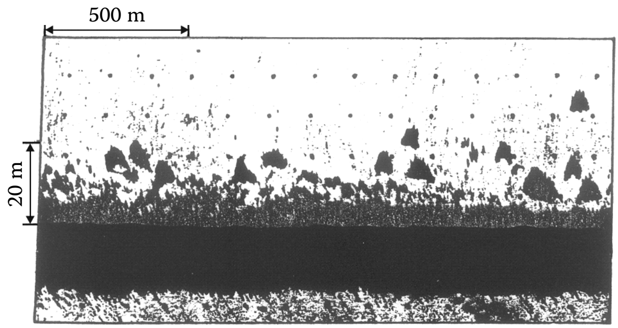

FIGURE 5.4 Recording of cod schools and concentrations in the Barents Sea (range, 120 m).

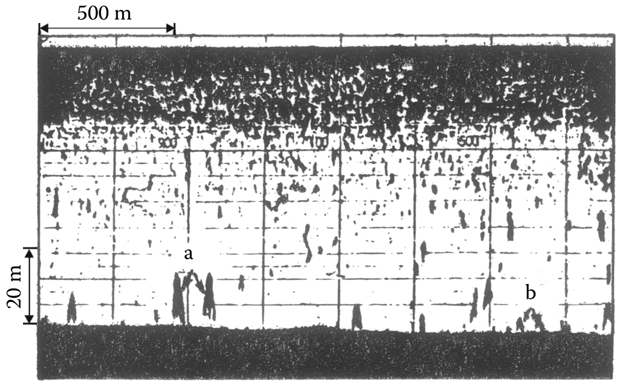

FIGURE 5.5 Recording of herring and sprat schools in the North Sea (range, 150 m): a, herring; b, sprat.

cod schools, unlike those of herring, have indistinct, diffuse outlines. Recordings of herring also differ noticeably from those of sprat. On the echogram of sprat, little distinct schools are represented, much smaller than schools of herring (Figure 5.5). Some differences have been observed between recordings of schools of horse mackerel and sardines on the shelf of Africa. Recordings of schools of horse mackerel, unlike those of sardine, had a more regular shape, with more distinct borders. Commercial concentrations of various fish can be registered differently. It is easy to differentiate concentrations of large fish from those of small ones. Recordings of concentrations of cod, sea perch, and other large fish have a "friable" form and low intensity (Figure 5.6). Concentrations of small fish (herring, sprat, and others) are usually registered as layers of high intensity. Concentrations of young fish give especially dense recordings (Figure 5.7).

Species interpretation of mixed concentrations including several fish species presents considerable difficulties. The knowledge of the character of daily vertical migrations of various fish species can be helpful in elucidating the species composition of concentrations in some cases. During such migrations, one may often observe the division of commercial fish concentrations into layers. Thus, in the area

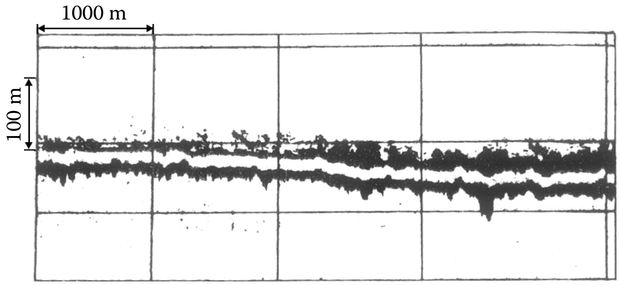

FIGURE 5.6 Recording of the bottom concentration of sea perch before spawn in the area of the island of Newfoundland (range, 400–900 m).

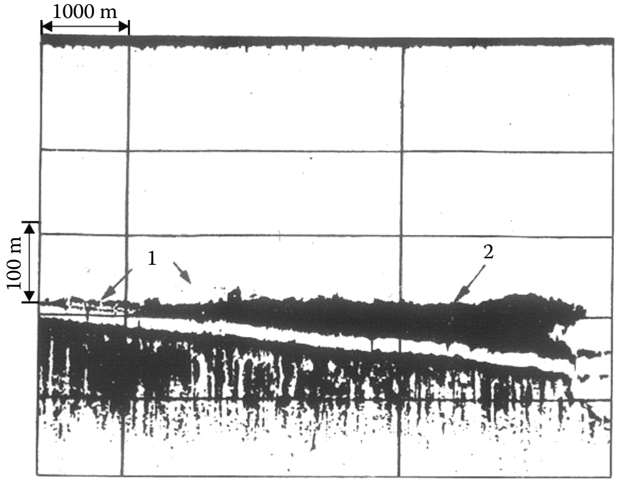

FIGURE 5.7 Recording of the bottom concentration of sea perch on the bank of the Flemish Cap (range, 500 m): 1, young fish; 2, adult specimens.

of the island of Newfoundland, anchovy can separate from perch concentrations during the movement of the fish to the upper water layers; the anchovy are registered as a continuous, inclined band (Figure 5.8). The division of fish concentrations into layers is observed in Caspian sprat during the evening and at night when, depending on fish biological conditions, a concentration is divided into three or four layers.

It is especially important to take into account such factors as water temperature, depth, and bottom relief in the search and interpretation of fish that keep near the bottom and are poorly registered by acoustic instruments. In the area of the island of Newfoundland, it is possible to make a judgment about the species composition of registered concentrations (perch or cod) depending on the depth (isobaths) where the recording is obtained. Knowledge of the character of the bottom is also helpful in the interpretation of readings. The presence of fish readings over rocky ground provides complete certainty in determining the fish species in the areas of perch fishing of the Far East. When fish hug the ground and are not registered by instru-

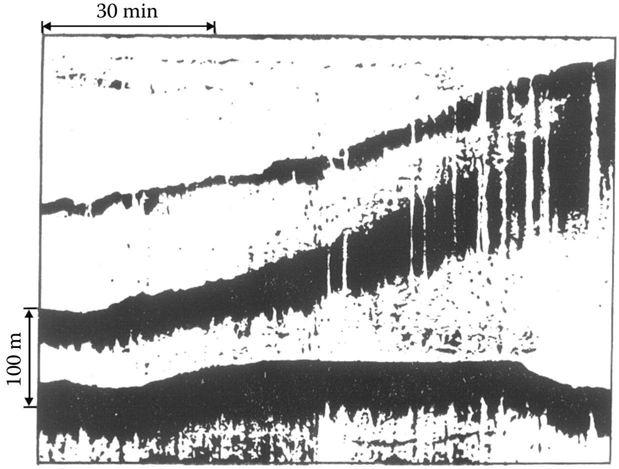

FIGURE 5.8 Recording of the evening elevation of anchovy (upper layer) and sea perch (bottom layer) in the area of the island of Newfoundland (range, 600 m).

ments, their search is often carried out by the isobaths only. For instance, in the area of halibut fisheries in the Far East, one searches by the depth and the character of the relief of the bottom; the presence of a complex bottom relief abounding in rocks and canyons indicates the possibility of halibut concentrations.

For elucidating the nature of unrecognized readings of fish-finding instruments, different means of observations (underwater TV, photography) can be used. It is possible to interpret acoustic readings according to the character of sounds produced by fish. However, the main method continues to be control fishing; comparison of species echo recordings with the composition of catches, stomach contents of fish caught, and plankton concentrations give reliable results. In this connection, the influence of fish distribution and physiological conditions on their behavior relative to different fishing gear should be obligatorily taken into consideration.

The practice of trawling shows that in registering schooled fish, the value of catches does not often correspond to the intensity of acoustic readings; and in contrast, catches correspond well with readings from a dispersed fish distribution. This is explained by the fact that schools actively react to the approach of a trawl; therefore, they leave the area faster than dispersed fish. Non-mobile wintering and spawning concentrations, as well as fish just after the spawn, are especially easily subjected to fishing by a trawl. As they sexually mature, fish become more movable and sensitive regarding active fishing gear.

The reverse picture is observed with the use of drift nets. Correspondence of readings with catches usually takes place with a schooled fish distribution; with non-mobile concentrations of great number, fish readings may not coincide with catches.

As follows from all of the above-mentioned, the solution of the problem of species interpretation of readings of acoustic instruments is connected to the revelation of the entire complex of biological dependences between fish and medium. In particular, it is necessary to know to what extent physical and biological factors of the environment (temperature, salinity, food sources) affect the general distribution, the structure of formation of concentrations, the character of daily vertical migrations, and so on, and all this regarding each species of fish inhabiting a body of water during its whole life cycle.

It is clear that the possibilities of species interpretation of readings depend greatly on the degree to which a body of water has been studied. In this sense, all sorts of manuals and textbooks of searches and interpretations of readings of acoustic instruments, as well as sketchbooks of typical echograms, have been very helpful during the mastering of commercial regions.

Further improvement of methods of species interpretation of readings consists of the accumulation of observations of the distribution and structure of various concentrations, the revelation of new biological regularities connected to the impact of the water medium on the character of fish distribution, as well as the elaboration of instrumental methods of direct determination of the species composition of fish concentrations registered by acoustic instruments.

5.2 SPECIES AND SIZE INTERPRETATION OF RECORDINGS BY INSTRUMENTAL METHODS

With the intense modern fisheries over shelves, when stricter limitations of catches are introduced, it is important to avoid trawls that do not produce a predetermined variety of catches. This means that remote methods of species and length interpretation of commercial concentrations must be correct. Therefore, great attention has lately been paid to the development of instrumental methods of species and length interpretation of concentrations without their being fished.

To more clearly imagine the possibilities for the further improvement of methods of interpretation of recordings of commercial concentrations, let us address an analogous subject in the animal world, location by sound, which is investigated by biophysicists. Studies of animals having a sound location apparatus show that echo signals received by them can contain information on the species and on the sizes of reflecting items. Thus, for instance, dolphins and bats both possess significant possibilities for the revelation of qualitative differences in echo signals from various items. They are able to differentiate required echoes from background ones even though the amplitude of useful signals is dozens of times weaker than that of the disturbing noises. At present, it has not yet been clarified just how these animals differentiate between echoes from various targets. However, some substantial advantages of sound locators of dolphins and bats compared to the modern sonar have been established during the investigations of their apparatus.

One of the main qualities of sound locators of animals is that they are able to produce and interpret a wide spectrum of acoustic waves. It is obvious that, with a multifrequency signal, an echo carries a broader spectrum of information on a reflecting object. Biophysicists noticed the same quality of multifrequency signal in carrying out experiments with blind people. Investigators established that blind people use artificial noise, with its wide spectrum of frequencies, for detecting obstacles more efficiently than can be done with simple tones.

There is no doubt that the application of equipment operating at a wide range of frequencies promises great possibilities in interpreting commercial concentrations, especially by the resonance of a fish swim bladder. In accordance with the modern theory of sound scattering,[2,3] the frequency dependence of the fish acoustic section can serve as a precondition to it. The dependence of the target strength on frequency is depicted schematically in Figure 5.9 (let us remember that the target strength is a logarithmic measure of the acoustic section).

It has already been mentioned in Section 1.2 that, at low sound frequencies, when sizes of a fish are significantly smaller than the wavelength, the acoustic section grows in proportion to the frequency raised to the fourth power. Then the acoustic section reaches a maximum at the resonance frequency of its swim bladder. The value of this frequency is determined theoretically in the same way as that regarding a free air bladder[4]:

$$f_{res} = \left(10^{-3}\sqrt{p_{stat} + \mu_{shift}}\right)/r_{bl} \tag{5.1}$$

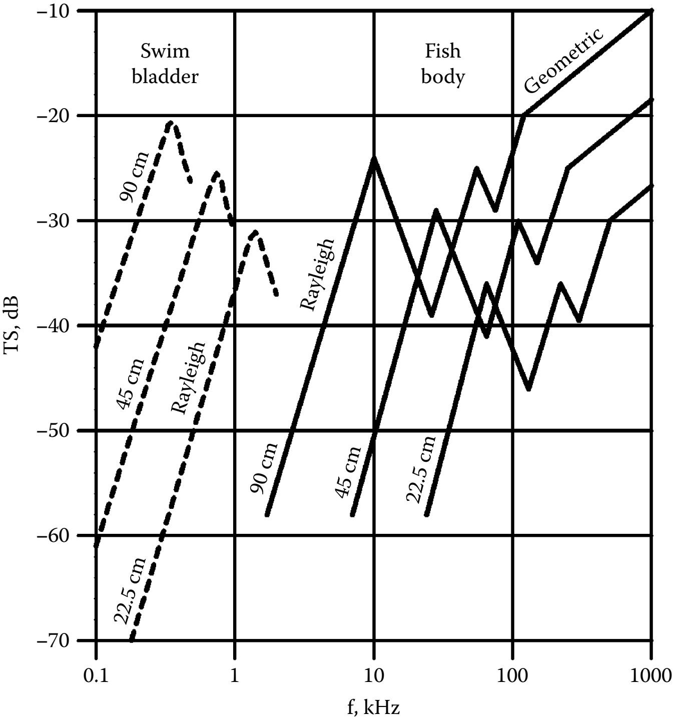

FIGURE 5.9 Relationship between the target strength and frequency regarding fish 22.5, 45.0, and 90.0 cm long at a depth of 90 m (the dashed lines show the corresponding dependences for the free swim bladders).

where f_{res} is the resonance acoustic frequency, kHz; r_{bl} is the radius of a sphere equal to the cavity of a swim bladder by volume, cm; p_{stat} is the static pressure at the inhabiting depth of a fish, N/m^2; and μ_{shift} is the module of the shear of fish body tissues encircled by a swim bladder, N/m^2.

It has been established that the value μ_{shift} is proportional to the square of the operation frequency; with $f = 10$ kHz, $\mu_{shift} = 10^4$ N/m^2.

With increasing the frequency higher than the resonant one and with an invariable size of fish, a decrease in the acoustic section is first observed and then its gradual increase.

At higher frequencies, when fish dimensions are comparable with the wavelength, the acoustic section must have maxima and minima. This is explained by interference phenomena, which occur as a result of superposition of reflections inside a fish. The maxima of reflection in registering large fish at comparatively low frequencies, and small fish at higher ones, indicate the existence of optimal operation frequencies regarding various fish sizes and species.

As already mentioned in the first chapter, experimental investigations at ultrasonic frequencies would not confirm these theoretical preconditions, as abrupt frequency dependences of fish reflectivity have so far not been clarified. However, it has been established that various fish sizes and species have their own envelope of echo signals at different frequencies. These differences in the fish frequency characteristics indicate that there is a possibility of solving a problem of the species and length interpretations of recordings with the help of the multifrequency ultrasonic equipment.

Work on using the multifrequency ultrasonic equipment for species and length interpretations of recordings provided good results. Experiments in net cages show that cod, saithe, herring, and scomber of similar length differ among themselves by the spectrum of echo signals.[5]

The use of the resonance of a swim bladder is another way of solving the problem of the species interpretation of readings of commercial concentrations. Unlike the interferential zone, strongly pronounced maxima of the reflection at the resonance of a swim bladder (Figure 5.9) have been proved theoretically and experimentally.[6,7] If a fish concentration is insonified by wide band signals at the determined range of frequencies, then, by an increase of levels in the spectrum of echoes, it is possible to find values of resonance frequencies of swim bladders. In turn, in using these frequencies, the dimensions of swim bladders can be determined; the latter is connected to the fish length by the empirical relationship.*

The range of fish lengths determines the width of the frequency spectrum at which an increase in levels of echo signals is observed. As follows from formula (5.1), the resonance of a swim bladder of commercial fish can be observed within a range of frequencies from hundreds of Hz to several kHz. The dependence of the resonance frequency on the length of swim bladder fish of different species has been verified experimentally.[8] Such an empirical dependence is presented in Figure 5.10. As seen from the graph, the dispersion of data regarding different species is not great.

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* It is probable that, in the future, fish dimensions will be determined with the help of wideband frequency equipment at sound frequencies in the range of the resonance of a swim bladder, while the species of fish will be determined by ultrasonic frequencies in the area of interferential reflections.

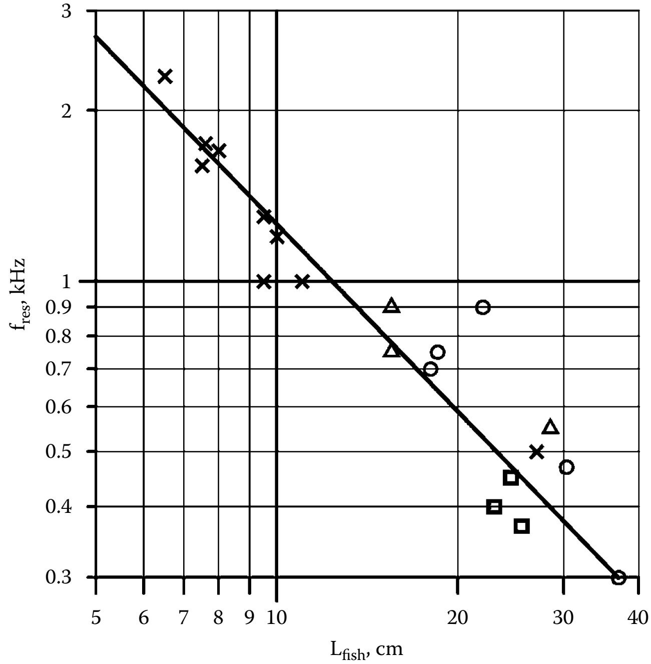

FIGURE 5.10 Dependence of the resonance frequency on the length of bladder fish (the symbols x, □, Δ, o show the experimental data for various species).

To elucidate the practical possibilities of determining dimensions of fish by the spectral characteristics of their echo signals, experimental investigations on various species of swim bladder fish have been carried out.[7,9,10] For this purpose, special equipment was developed; this equipment included a powerful generator (required for covering a high level of the low frequency noise of a vessel), insonifying and receiving transducer, amplifier, and registering devices.

The experimental conditions on the commercial concentrations at sea were controlled with the help of fish-finding echo sounders. The measured spectral characteristics of echo signals from the commercial concentrations were compared with the rated frequency dependences of acoustic sections of the fish length series received as a result of the control fishing of the concentrations under study. The fish acoustic sections near their swim bladder resonance were calculated from the following formula[6]:

$$\sigma = \frac{r_{bl}^2 Q_{bl}^2}{\left[\left(f_{res}/f\right)^2 - 1\right]^2 Q_{bl}^2 + \left(f_{res}/f\right)^2} \tag{5.2}$$

where Q_{bl} is the quality of the swim bladder.

The quality of a swim bladder is minimal at the water surface, where the value Q_{bl} does not exceed 2.0–3.0, and rises several times with increases of depth.

The calculated acoustic sections, taking into account the length series of the fish caught, allowed receipt of the spectral characteristics of the concentrations under investigation. The results of calculations and measurements proved themselves to be quite comparable for all of the experiments, which testifies to the possibility of determining the length composition of fish concentrations by the considered method.[8]

It should be noted, however, that elaboration of the low-frequency wideband equipment is still fraught with technical difficulties, especially concerning reception of sound signals.* This problem hampers the inculcation of such instruments into the fisheries industry; the solution of the problem of the species interpretation of commercial concentrations by their frequency characteristics will be delayed until these technical difficulties have been satisfactorily addressed.

Investigations on the application of the energetic characteristics of echo signals for interpreting the readings of commercial items proved to be more efficient. In this plan, instrumental methods of determining the species item composition by the value of their target strength have already been elaborated and found practical application.

It has been shown in Section 1.2 that the dependences of the acoustic section (σ) on the length of a fish body L_{fish} regarding various species and groups of commercial items have been obtained during experimental investigations. Knowing such dependences, from the results of measuring the acoustic section, it is possible to determine dimensions of commercial items with the resolving registration when an acoustic instrument marks individual items separately. In measuring the acoustic section, it is necessary to calibrate the equipment (see Section 6.2) as well as taking into account or excluding the influence of transducer directivity characteristics on the results of measurements.

Taking into account or exclusion of the impact of transducer directivity characteristics on the results of estimating the acoustic section can be accomplished by the method of calculations or by the method of direct measurements. The method of calculations is used when the measurements of the acoustic section are carried out with the help of ordinary fish-finding echo sounders with a standard wide-beam transducer; they ensure by mathematical means the correction of the distribution of echo signals from commercial items with consideration of their random location within the detection zone of an echo sounder. If the direct methods are used, the correction of transducer directivity characteristics is accomplished by the corresponding technical means.

Several methods of calculations in determining the acoustic section have been elaborated. The method of Craig and Forbes is the most widely used.[11] Its essence consists in the following. Echo signals from individual commercial items are divided, by amplitude, onto several groups. The transducer directivity diagram is divided onto the same number of levels. Then the system of equations for determining the item target strength in each gradation is worked out and solved proceeding from the number of echo signals in each group and taking into account the data of calibration of the equipment. The distribution of the acoustic sections is represented on the display and printer after treating the data with a microprocessor according to the method of Craig and Forbes. Comparison of results of measurements with the data of trawling catches has shown the admissible correspondence of the distributions of acoustic sections with the length distribution obtained as a result of fishing.

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* In perspective, the possibility of elaborating multifrequency instruments on the basis of frequency-modulated and complex signals is foreseen.

Among the other models, it should be noted that instruments using direct methods of compensation for the influence of transducer directivity characteristics on results of measurements give more precise results in determining the target strength and the length composition of commercial concentrations. The dual-beam, conic-beam, and split-beam equipment are among such models.

The dual-beam equipment has narrow- and wide-beam transducers, operating along one axis or situated close to one another.[12] Insonification is accomplished by the narrow-beam transducer; the reception is accomplished by both transducers. Therefore, the appearance of echo signals and measuring the acoustic section are only possible near the axis of the acoustic systems when an object is located within the detection zone of the narrow-beam transducer. In the conic-beam equipment, the recalculation of the acoustic section onto the acoustic axis is not required, as the sensitivity of the instrument inside the detection zone is the same.[13] This is achieved through correction of the gain by the microprocessor regarding various sections of the transducer.

The elaboration of a split-beam echo sounder was first announced by Foote et al.[14]; since then, the split-beam equipment has found ever-growing application in fisheries (see, for instance, References 15–20 and other studies). Therefore, let us consider its possibilities in greater detail. The essence of the split-beam principle consists in the determination of the angle of inclination of commercial items from the acoustic axis with the help of the two coaxial receiving transducer elements, and the following calculation of the acoustic section taking into account the corresponding directivity factor. The transducer is divided into four quadrants, operating simultaneously and co-phasely when insonifying, and separately when receiving.

With moving a commercial item off the acoustic axis, echo signals at the input of receiving elements of a transducer arrive with different phases. By the difference of phases in two perpendicular planes, the microprocessor calculates the location of an item within the detection zone of an instrument, introduces the corresponding correction into an echo signal, and determines the target strength.* The software also provides for selection of commercial items against a background of disturbances according to the criterion of the temporal recognition of the duration of echo signals, which are within a value of 0.8–1.8 from the duration of a transmitted impulse.

The treatment of data and the determination of the species and weight composition of commercial items are accomplished within the limits of the layer of chosen depths. The values of target strength are accumulated, sorted by groups, and then the length distribution is calculated according to the equation chosen. The length of commercial items is transformed into relative values of biomass through the formula $W = KL_{fish}^3$. The coefficient of proportionality K is determined empirically. The percent distribution of the biomass, depending on the length of items, is represented on the display as a histogram.

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* Such equipment is used not only to measure the target strength of items and the species composition of commercial concentrations, but also to determine the direction and speed of their movement. These behavioral characteristics are important both in fisheries and in carrying out acoustic surveys for biomass estimation.

Marine tests of the instrument have shown a rather strong correspondence of the length and species distributions of commercial items received with the help of "Simrad" split-beam echo sounders and on the basis of catches. The results of two series of tests of the equipment conducted in the Barents Sea on cod concentrations are given in Figure 5.11. As seen from the figure, the mode of the length distribution received as a result of catches coincides with that appearing on the histogram of the instrument. However, no detailed coincidence is observed. In particular, the smaller dimensions of cod are seen on the histogram, but were absent in catches. This can be explained by fish behavior: because of the complicated characteristic of the sound scattering by fish, even small variations of the inclination angle of a fish body leads to changes in the target strength and, consequently, of dimensions measured of fish.

The shift to smaller values of fish dimensions on the histogram is also connected to the selectivity of the trawl used. Trawl selectivity is determined by the passive (filtration through a mesh) and active release of commercial items from a trawl, which varies depending on the speed of trawling and the character of the distribution of concentrations. As an example, some results of Norwegian studies of release of capelin from the trawl are shown in Figure 5.12.[21] It is seen in the figure that the trawl selectivity greatly depends on the dimensions of fish caught. For the sake of a correct comparison of the histogram of the length distribution of commercial items obtained with the help of instruments and that obtained through catches, it is necessary to know and to take into account the differential selectivity of trawls used.

The reliability of estimating the length distribution of items in commercial concentrations by instrumental means is determined by the error of the method of measuring the acoustic section (σ) and by the precision of the dependence $\sigma = f(L_{fish})$, which is used in treating data. As the acoustic section depends on many factors and, for the same item length can greatly differ during various periods of its life, in order to increase the reliability of interpreting concentrations, it is necessary to specify the dependence $\sigma = f(L_{fish})$ regarding various conditions of habitation of commercial items.

The instrumental species and length interpretation of commercial concentrations has presented itself in a good light aboard fisheries vessels. No doubt, an inculcation of this equipment will be very intensive in the near future, especially since this equipment is necessary for fishermen and investigators not only for determining the length and species composition, but also, as will be shown in further chapters, for the quantitative interpretation of concentrations for the estimation of their commercial significance and biomass.

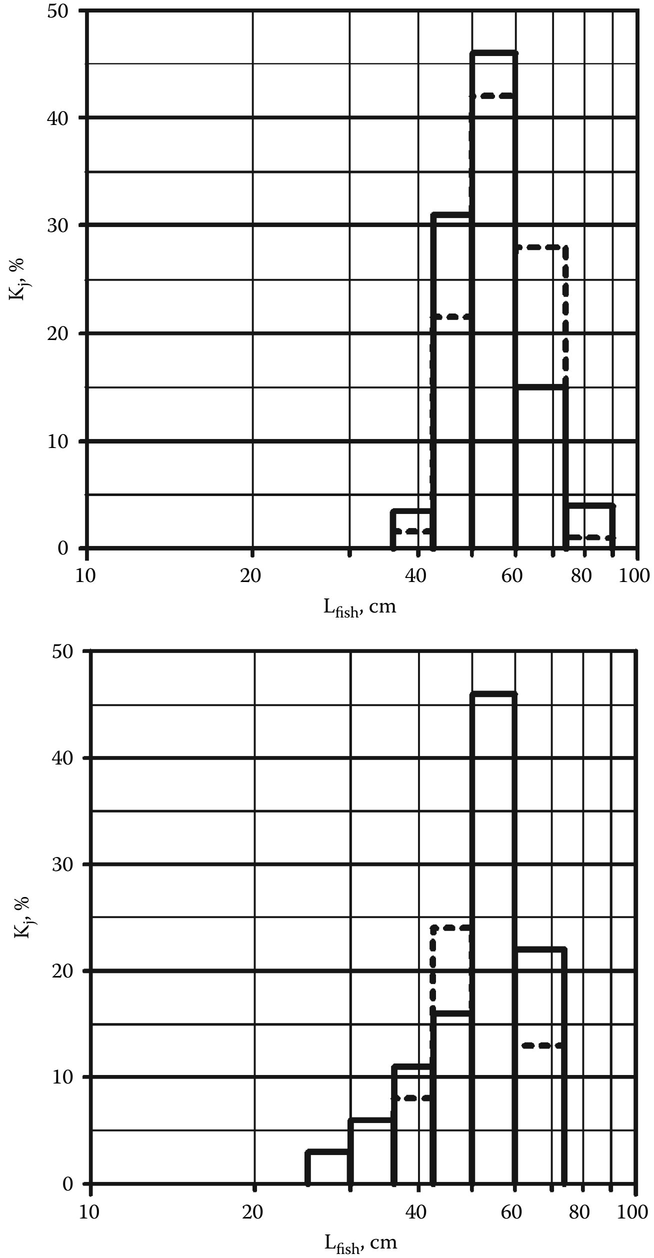

FIGURE 5.11 Histograms of the length composition of cod by trawling catches (top) and by "Simrad" split-beam equipment readings (bottom): solid line, results of the first series of tests; dashed line, results of the second one (Gavrilov, E.N., personal communication).

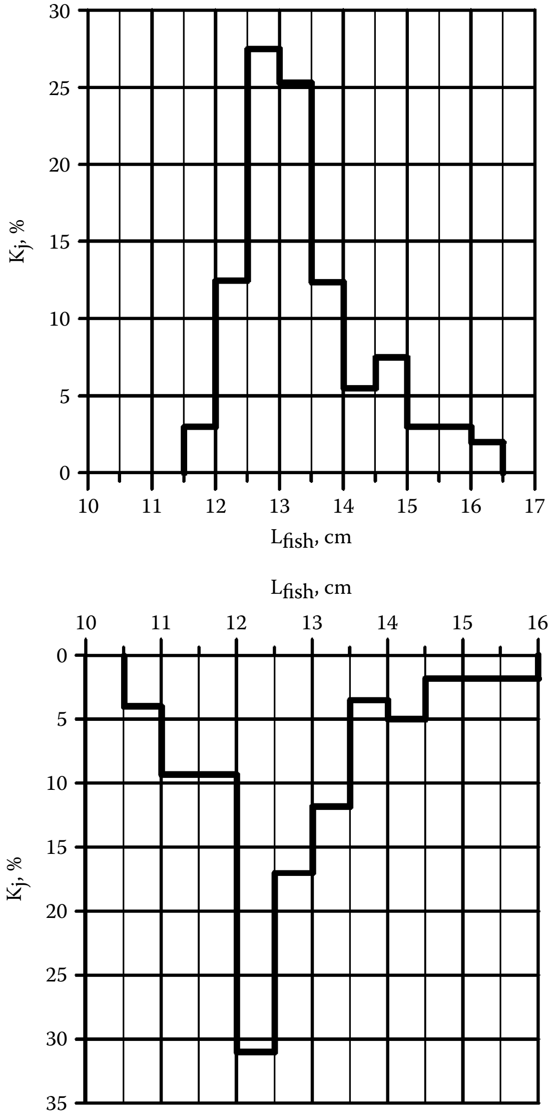

FIGURE 5.12 Length composition of capelin. Top: fell into the cod-end (the average length is 13.1 cm); Bottom: released from the trawl (the average length is 12.3 cm).

REFERENCES

1. Sverdrup, H.U., Johnson, M.W., and Fleming, R.H., *The Oceans. Their Physics, Chemistry, and General Biology*, Englewood Cliffs, N.J., Prentice-Hall, 1087, 1963.
2. Clay, C.S. and Medwin, H., *Acoustical Oceanography: Principles and Applications*, Wiley, New York, 1977.

3. Foote, K.G., Acoustic scattering by marine ecosystem, *Encyclopedia of Ocean Sciences*, 1(A–C), 44, 2001.
4. Andreeva, I.B. and Samovol'kin, V.G., *Sound Scattering by Sea Organisms*, Agropromizdat, Moscow, 102, 1986 (in Russian).
5. Simmonds, E.J. and Armstrong, F., A wideband echo sounder: Measurements on cod, saithe, herring and mackerel from 27 to 54 kHz, in Developments in Fisheries Acoustics. A Symposium Held in Seattle, 22–26 June 1987, Karp, W.A., Ed., *Rapports et Proces-Verbaux des Reunions*, 189, 381, 1990.
6. Andreeva, I.B., Scattering of sound by air bladder of fish in deep sound-scattering ocean layers, *Soviet Physics Acoustics*, 10, 17, 1964.
7. Lovik, A. and Novem, J.M., An experimental investigation of swimbladder resonance in fishes, *Journal of the Acoustical Society of America*, 66(3), 850, 1979.
8. Lovik, A., Olsen, K., and Dalen, J., Acoustic Remote Sensing of Fish Size, presented at International Symposium on Fisheries Acoustics, Bergen, Norway, 21–24 June 1982.
9. Holliday, D.V., The use of swimbladder resonance in the sizing of schooled pelagic fish, in Hydro-Acoustics in Fisheries Research, A Symposium Held in Bergen 19–22 June 1973, Margetts, A.R., Ed., *Rapports et Proces-Verbaux des Reunions*, 170, 130, 1977.
10. Kloser, R.J., Ryan, T., Sakov, P., Williams, A., and Koslow, J.A., Species identification in deep water using multiple acoustic frequencies, *Canadian Journal of Fisheries and Marine Science*, 59(6), 1065, 2002.
11. Craig, R.E. and Forbes, S.T., Design of a sonar for fish counting, *Fiskeridirektoratets Skrifter*, series "Havundersokelser," 15(3), 210, 1969.
12. Ehrenberg, J.E. and Lytle, D.W., Some signal processing technique for reducing the variance in stock abundance estimates, in Hydro-Acoustics in Fisheries Research. A Symposium Held in Bergen 19–22 June 1973, Margetts, A.R., Ed., *Rapports et Proces-Verbaux des Reunions*, 170, 205, 1977.
13. Sasakura, T., Minohara, K., and Kagawa, J., Scientific Sounder Using Quasi-Ideal Beam Transducer, presented at International Symposium on Fisheries Acoustics, Seattle, 22–26 June 1987.
14. Foote, K.G., Kristensen, F.H., and Solli, H., Trial of a new, split-beam echo sounder. Fish capture committee, International Council for the Exploration of the Sea, Copenhagen, Denmark CM 1984/B:21, 15, 1984.
15. Traynor, J.J. and Ehrenberg, J.E., Fish and standard-sphere target-strength measurements obtained with a dual-beam and split-beam echo-sounding system, in Developments in Fisheries Acoustics. A Symposium Held in Seattle, 22–26 June 1987, Karp, W.A., Ed., *Rapports et Proces-Verbaux des Reunions*, 189, 325, 1990.
16. Ehrenberg J.E. and Torkelson, T.C., Application of dual-beam and split-beam target tracking in fisheries acoustics, in Proceedings of an ICES International Symposium Held in Aberdeen, Scotland, 12–16 June 1995, Simmonds, E.J. and MacLennan, D.N., Eds., *ICES Journal of Marine Science*, 53(2), 329, 1996.
17. Soule, M., Barange, M., Solli, H., and Hampton, I., Performance of a new phase algorithm for discriminating between single and overlapping echoes in a split-beam echosounder, *ICES Journal of Marine Science*, 54(5), 934, 1997.
18. Bertrand, A., Jasse, E., and Masse, J., *In situ* acoustic target-strength measurement of bigeye (*Thunnus obesus*) and yellowfin tuna (*Thunnus albacares*) by coupling split-beam echosounder observations and sonic tracking, *ICES Journal of Marine Science*, 56(1), 51, 1999.

19. Torgersen, T. and Kaartvedt, S., *In situ* swimming behaviour of individual mesopelagic fish studied by split-beam echo target tracking, *ICES Journal of Marine Science*, 58(1), 346, 2001.
20. MacLennan, D.N., Copland, P.J., Armstrong, E., and Simmonds, E.J., Experiments on the discrimination of fish and seabed echoes, *ICES Journal of Marine Science*, 61(2), 201, 2004.
21. Dommasnes, A. and Roettingen, I., Acoustic stock measurements of the Barents Sea capelin 1972–1984, A review, in Proceedings of the Soviet-Norwegian Symposium on the Barents Sea Capelin (*Mallotus villosus*), Gjoesaeter, H., Ed., Institute of Marine Research, Bergen, Norway, 45, 1985.

6 Quantitative Interpretation of Recordings of Commercial Items

For the efficient use of acoustic instruments, not only the species and length structure, but also the quantitative composition of registered commercial concentrations, should be estimated. The quantitative estimation of readings of acoustic instruments is important in determining fisheries resources, in studying biological regularities of the distribution and behavior of aquatic animals, and in fisheries for detecting the densest areas of concentrations and their targeted catching.

6.1 THEORETICAL QUESTIONS OF DETERMINING THE DENSITY OF COMMERCIAL CONCENTRATIONS

The basis of the acoustic method of estimating commercial concentrations constitutes the following, universally recognized, statement: The energy of echo signals is proportional to the density of distribution of biological items with the Rayleigh sound scattering, which occurs in the overwhelming majority of practical cases (see Section 1.3).* Measurement of the energy of echo signals is made with the help of an echo integrator. Our studies have shown that the theory of the process of echo integration is single, both in cases of resolving and unresolving fish registration by acoustic instruments.[2] This thesis has been repeatedly confirmed by experimental measurements on dense concentrations of small fish in net cages and with dispersed concentrations of large fish, the density of which were determined by echo counting.

The formula for determining the value of readings of an echo integrator for one transmission with registering concentrations of various densities has the following look[2]:

$$M_1 = C_{ea}\rho_v\sigma h\Psi \tag{6.1}$$

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* The acoustic method of quantitative estimation of commercial concentrations was initially suggested in the work of Yudanov.[1]

where C_{ea} is the electro-acoustical constant of the equipment, P_v is the volume concentration density, h is the concentration thickness, and Ψ is the integral directivity factor.

In this formula, only the integral directivity factor changes in transition from a dispersed concentration to a dense one. It can be seen from relation (6.1) that the readings of an integrator, and, consequently, the square of the envelope of an echo signal are proportional to the integral directivity factor. As follows from Figure 4.3, the maximal, amplitude values of the echo signal envelope U_{amp} correspond to the maximum of the integral directivity factor $\Psi(0,\theta_{amp})$ at the moment when the impulse volume reaches the lower border of a concentration. The threshold, minimally required for the item registration, values of the envelope U_{min}, appearing at the beginning (with θ_{min}) and end (with θ_{max}) of the registration of echo signals at the border of the detection zone, determine the minimally required integral factors, the central $\Psi(0,\theta_{min})$ and peripheral $\Psi(\theta_{eff},\theta_{max})$ ones; i.e.,

$$\Psi(0,\theta_{min}) = \Psi(\theta_{eff},\theta_{max}) = \Psi(0,\theta_{amp})\,\frac{U_{min}^{\;2}}{U_{amp}^{\;2}} \tag{6.2}$$

Thus, the measurement of amplitudes of echo signals allows for determining the values of θ_{min}, θ_{amp}, and θ_{max} with a uniform distribution of commercial items in a concentration. At the same time, the distances r_{cen} and r_{per} are determined, from which the central and peripheral threshold echo signals arrive. The following relation determines the effective value of the integral directivity factor in registering a concentration[2]:

$$\Psi = \left[\int_{r_{cen}}^{r_{per}} \Psi\left(\theta_1,\theta_2\right)dr\right]/h \tag{6.3}$$

where θ_1 and θ_2 are the width of the beam of an instrument, corresponding to the current distance r to the impulse volume, and r_{cen} and r_{per} are the distances, from which the threshold echo signals arrive.

The value $\Psi(\theta_1,\theta_2)$ is determined as a difference of the values of the integral directivity factor, corresponding to θ_1 and θ_2:

$$\Psi(\theta) = \int_0^{2\pi}\int_{\theta/2}^{\pi/2} G\left(\theta,\varphi\right)\ \sin(\theta/2)d(\theta/2)d\varphi \tag{6.4}$$

where $G(\theta,\varphi)$ is the directivity function of the acoustic beam by intensity.

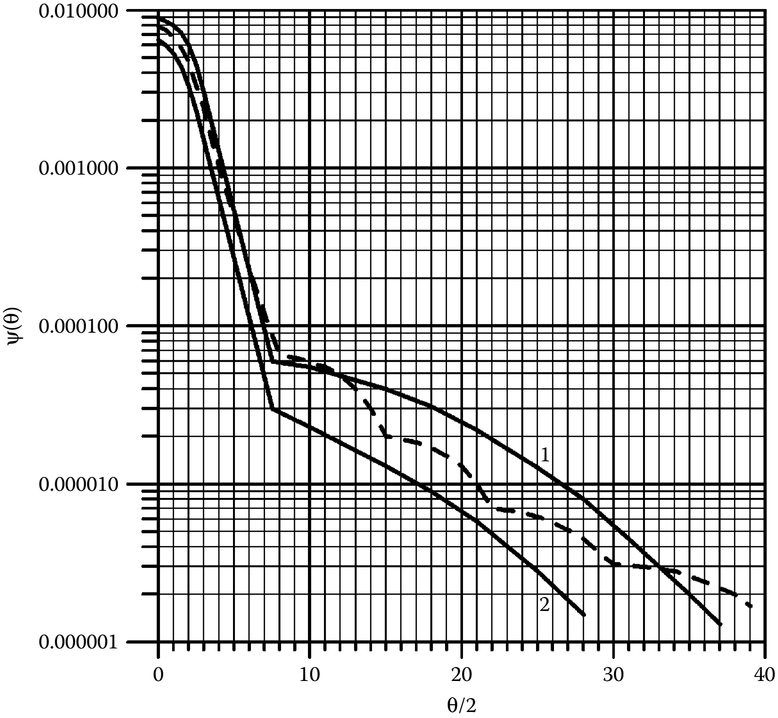

FIGURE 6.1 Integral diagrams of directivity of the different sound types of "Simrad" transducers, determined for various conditions. Solid line: transducer type ES 38B, operating at 38 kHz (1, calculated by usual method; 2, calculated taking into account the backscattering by herring 22.5 cm long); dashed line: transducer type ES 120-7C, operating at 120 kHz.

In Figure 6.1, the diagrams are given of the integral directivity functions of "Simrad" transducers operating at various frequencies, determined from expression (6.4). The effective value of the integral directivity factor is calculated from formula (6.3). Kalikhman and Tesler accomplished these calculations[3]; let us consider their results.

The dependences of the ratio of active integral factor Ψ to its full certificate value Ψ_{full} on the dynamic range of registered echo signals U_{amp}/U_{min} are given in Figure 6.2. These dependences, as well as calculations with the other distances to concentrations, show that with increasing the concentration thickness and decreasing its depth, the integral factor rapidly approaches the constant, certificate value.

Calculations regarding wide- and narrow-beam acoustic instruments indicate that in all the real cases of registering concentrations of items, unresolved by instruments, it is possible to use the certificate value of the directivity factor (curve 2). The error of echo integrator readings because of the substitution of Ψ by Ψ_{full} in this case does not exceed 10%. With resolving registration of concentrations, the dependence of $\Psi/\Psi_{full} = f(U_{amp}/U_{min})$ is practically the same for both wide- and narrow-beam acoustic instruments. It follows from curve (1) that the use of the

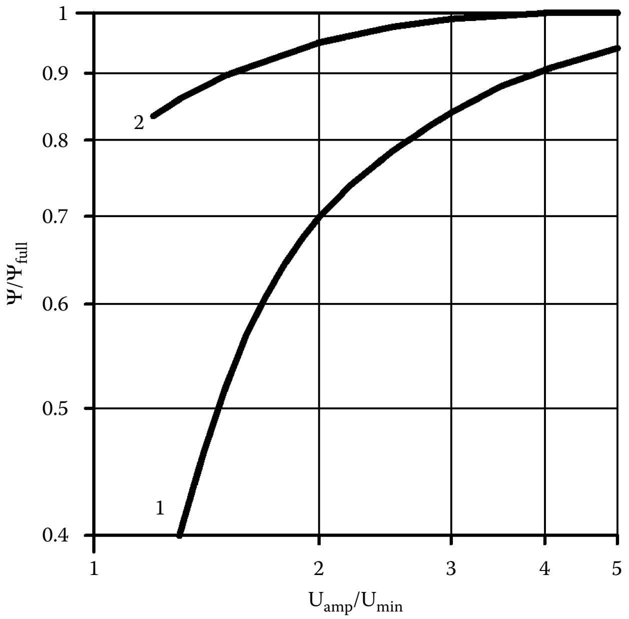

FIGURE 6.2 Dependence of the integral directivity factor on the dynamic range of echo signals in regard to registering various targets: 1, individual; 2, multiple.

certificate parameter Ψ_{full} is admissible with $U_{amp}/U_{min} > 4.0$. With a smaller dynamic range of registered echo signals, it is necessary to determine the Ψ value regarding specific conditions of target registration.

Going back to expression (6.1), we obtain the following generalized formula for estimating the volume concentration density (in sp/m^3):

$$\rho_v = \frac{M_1}{C_{ea} h \Psi \sigma} \tag{6.5}$$

or

$$m_v = \rho_v \sigma = \frac{M_1}{C_{ea} h \Psi} \tag{6.6}$$

The volume density ρ_v is used in studying the structure of commercial concentrations, their distribution by area and depth. Regarding the estimation of biomass of commercial concentrations, it is more convenient to use the area density ρ_s (in tons/mile^2)

$$\rho_s = 3.4 w h \rho_v \tag{6.7}$$

where w is the mass of an individual item, g.

Substituting formula (6.7) into expression (6.5), we obtain

$$\rho_s = \frac{3.4wM_1}{C_{ea}\Psi\sigma} \tag{6.8}$$

In calculating the logarithm of equations, which is widely used in fisheries acoustics, formula (6.8) takes the following look:[4]

$$10\log\rho_s = 10\log M - 10\log C_{ES} - 10\log C_{EI} - TS \tag{6.9}$$

where C_{ES} is the constant of a fish finding instrument (including the integral directivity factor) and C_{EI} is the constant of an echo integrator.

Formulas (6.8) and (6.9) are the basis for determining the density of commercial concentrations by the method of echo integration; in fact, they are algorithms of the computer treatment of survey data.

With separate fish registration by an acoustic instrument, it is possible to measure the density of concentrations by echo counter readings.[5] In this case, the following formula is used for calculations[2]:

$$\rho_s = \frac{n_{echo}}{k_f r^2 \theta_{eff}^2 n} \tag{6.10}$$

where n is the number of transmissions (pings).

In formulas (6.8)–(6.10), we ignored the multiple and coherent sound scattering in fish concentrations. In Chapter 1, we have already considered conditions when the coherent and multiple sound scattering can be neglected. Let us consider this question in greater detail.

The analysis of the phenomena of sound propagation in dense fish concentrations, cited in section 1.3, shows that the conditions, when it is possible to neglect the coherent component of scattering, can be found from formula (1.25):

$$\rho_v < \frac{8c\tau}{\pi\lambda^2 r^2 \theta_{eff}^2} \tag{6.11}$$

For an echo sounder with $c\tau = 1.5$ m, $\lambda = 5.0$ cm (the operation frequency f = 30 kHz), r = 100 m, and $\theta_{eff} = 0.17$ rad (10°), we obtain the limiting concentration density $\rho_v < 3.8$ sp/m^3. With r = 25 m, $\rho_v < 61$ sp/m^3.

The conditions, when it is possible to neglect the multiple component of scattering, can be found from formula (1.27):

$$\rho_v < \frac{0.8}{c\tau L_{fish}^2} \tag{6.12}$$

If a concentration consists of fish with the length $L_{fish} = 0.4$ m, then with the speed of sound c = 1500 m/s and the duration of locating pings of an echo sounder $\tau = 1.0$ ms, $\rho_v < 3.3$ sp/m^3. With $L_{fish} = 0.1$ m, $\rho_v < 53$ sp/m^3.

To have an idea as to the order of the possible density of concentrations, let us cite their tentative values regarding various species of marine animals (Table 6.1). These values have been received as a result of comparing the dimensions of concentrations registered by instruments and by their actual catches, as well as on the basis of the analysis of data of underwater observations.

It follows from conditions (6.11) and (6.12) and from the data cited in the table that it is possible to neglect the phenomena of the coherent and multiple scattering in estimating the density of concentrations of comparatively large fish. In the case of very dense schools and concentrations, to exclude the impact of these types of scattering, it is necessary, when estimating their density, to use echo sounders with a high operation frequency (up to 200 kHz), narrow transducer directivity characteristics, and short locating pings (up to 0.1 ms).

Analyzing the parameters forming expression (6.8), we can see that they may change greatly during the measurements of the density of concentrations in a commercial region. The value of the acoustic section of commercial items, depending on their depth and orientation relative to the ultrasonic beam of an acoustic instrument, is subjected to especially abrupt variations. The change in the item orientation has an impact on the integral directivity factor. The value of attenuation of acoustic signals in upper water layers changes strongly under various weather conditions.

TABLE 6.1
The density of concentrations of marine animals

Animal Species	Dimensions, cm	Density, sp/m^3
Plankton (large forms)	1–5	
Dispersed		10^{-1} to 10^{1}
Schools		10^{2} to 10^{4}
Concentrations		10^{1} to 10^{4}
Small fish (sprat, herring, and others)	5–25	
Dispersed		10^{-3} to 10^{-1}
Schools		10^{0} to 10^{2}
Concentrations		10^{-1} to 10^{2}
Large fish (cod, perch, and others)	25–100	
Dispersed		10^{-5} to 10^{-3}
Schools		10^{-2} to 10^{0}
Concentrations		10^{-3} to 10^{0}
Tuna, sharks, and other large animals	> 100	
Dispersed		$< 10^{-4}$

The variability of the cited parameters is strongly displayed with the horizontal item location and comparatively weekly with the vertical one. For this reason, the estimation of the commercial concentration density has been accomplished up to now, nearly exclusively by echo sounders. Questions of calibrating the equipment for determining the density and biomass of concentrations are described regarding echo sounders (except Section 6.4).

6.2 METHODS OF CALIBRATION OF ACOUSTIC INSTRUMENTS

Calibration of the acoustic equipment for the quantitative estimation of concentrations of fish and other marine items represents a complex of steps, carried out for the purpose of determining the main parameters of the equipment and for controlling their stability. Erroneous values of the characteristics of equipment, items under study and the environment may lead to an inadmissibly great error in the quantitative estimate of concentrations. Therefore, thorough calibration is one of the most important operations in determining the density of item concentrations.

Different methods of calibration of acoustic equipment have been elaborated.[6] As a result, the value of the scale for a recorder of the density of fish concentrations (integrator or counter) is determined.

The general constant of calibration or the scale value for an integrator (in tons/mile^2) can be determined from formula (6.8):

$$C = \frac{\rho_s}{M_1} = \frac{3.4\,w}{C_{ea}\,\Psi\sigma} \tag{6.13}$$

Once all of the parameters forming expression (6.13) are determined, it is easy to calculate the value of the scale; i.e., the density causing a unit reading of an integrator or some other registering instrument. Such a method of the separate determination of parameters is referred to as the step-by-step method of calibration.

Unlike the step-by-step calibration, "through" methods of calibration by commercial concentrations can be used; in this case, the density of concentrations is estimated by various means and the general constant of calibration is determined.

If a group of vessels with calibrated equipment work in one commercial region, the comparison of the results of calibration between different vessels through, so-called, intercalibration is conducted for reliable use of data of measuring the density.

Let us consider the main peculiarities of the step-by-step and through methods of calibration of the equipment, as well as of their intercalibration.

STEP-BY-STEP CALIBRATION

It follows from formula (6.13) that for calculating the value of the scale of an integrator, it is necessary to know the following parameters: the electro-acoustic constant of the equipment, the mass and reflectivity of an individual item, and the integral directivity factor of an acoustic beam. The electro-acoustic constant characterizes the technical condition of the transmitter and receiver of an acoustical instrument. This value is measured by the integration of echo signals from a standard sphere.[7] The electro-acoustic constant is calculated from the following formula[8]:

$$C_{ea} = \frac{4\pi r^2 M_1}{\sigma_{sph}} \tag{6.14}$$

where r is the distance to a standard sphere and σ_{sph} is the acoustic section of a sphere.

The standard sphere should be aligned strictly along the acoustic axis of a transducer during the measurements. The drift of a vessel and currents disturb precise alignment of the sphere. Therefore, the measurements are carried out in a closed bay; the work is conducted in the open sea only in extreme cases. In using split-beam equipment, where the impact of the transducer directivity characteristic on the results of measurements is compensated, the procedure is significantly simplified. The principles of operation of this equipment are considered in Section 5.2.

In aligning a standard sphere accurately on the axis of the ultrasonic beam, the precision of measurements of the electro-acoustic constant C_{ea} depends on the errors of an integrator, errors of calibrating the sphere, and the values of the spatial sound attenuation used in TVG. The errors of measurement of the value C_{ea} are usually not greater than ±20% (up to 0.9 dB).[9]

Commercial concentrations consist of items of various masses. In calculations, an average mass is used, which is determined from the results of control fishing. Regarding a mixed concentration, the average values of an individual item of each species and length group must be found. To increase the precision of such estimates, it is desirable to take into account the differential selectivity of trawls used.

Fish of various species and lengths are usually localized in different parts of a commercial concentration; thus, the fish distribution is nonuniform throughout the water area. Therefore, the control fishing is conducted at various places along the path of a survey. From the result of each catch, the average mass of items of each species and length group is determined.

As has already been mentioned in the previous section of the chapter, the value of the integral directivity factor Ψ weakly depends on the conditions of registration of a multiple target; it is practically equal to the certificate value. In this case, the integral directivity factor can be determined from the following formulas regarding transducers either with a round or rectangular aperture[10]:

$$\psi = 2\lambda^2/(\pi d^2)$$

or

$$\psi = 3\lambda^2/(2\pi ab) \tag{6.15}$$

where d is the effective diameter of a round transducer and a and b are the effective dimensions of a rectangular transducer.

The errors of the value of the integral directivity factor can be within the limits ±20% (up to 0.9 dB). The expression (6.15) does not take into account the nonuniformity of sound scattering by items under study. Accounting for this nonuniformity has, so far, been connected with practical difficulties.[3] This circumstance leads to an additional overestimation of the value of the integral directivity factor of up to 30% (1.1 dB) with the wide directivity diagram (on the order 20°).[9]

If a precise value of the integral directivity factor is required (as, for instance, in calculating the zones of detecting commercial items by an acoustic instrument), the numerical integration is carried out from formula (6.4).

Measurements of the acoustic section of an individual item (σ) are the most complicated step of the calibration. It has already been shown in the first chapter that the acoustic section depends, to a great degree, upon the behavior, the biological state, and conditions of habitation of commercial items; with varying body orientation, state of sexual products, or fattiness of the volume of a swim bladder, the real acoustic section can change considerably. Therefore, experimental data on acoustic sections regarding fish of various species and lengths, determined under stationary conditions, usually differ greatly from real ones. For determining real acoustic sections, measurements, at present, are carried out only at sea (*in situ*).

It has already been mentioned in Section 5.2 that for determining the value of acoustic sections *in situ*, special equipment based on the calculated and direct methods of measurements is applied. Such equipment ensures the microprocessor treatment of measurement data and represents the distribution of acoustic sections of items under study on a color display.

As commercial items are distributed nonuniformly throughout the water area, measurements of acoustic sections are carried out in various parts of the region under survey. As a rule, measurements of acoustic sections are conducted simultaneously with the control fishing in a layer, corresponding to the vertical opening of a trawl. The precision of sea measurements of acoustic sections is determined by the error of the equipment under use, as well as by the peculiarities of the behavior and distribution of items. The resulting error may reach ±20% and more.[9]

The determination of acoustic sections of commercial items *in situ* is carried out on dispersed concentrations only, in which the indicator of an acoustic instrument marks individual items separately. These are, first of all, concentrations of large fish (cod, perch, and others), which, in most cases, keep dispersed. Regarding concentrations of small fish (herring, sprat, and others), the dispersed distribution is not typical; it may, however, occur in rare cases. A resolving registration of small fish is possible at night, when fish or concentrations, performing vertical migrations, disperse in the upper layers of the water.* Sometimes, small fish are registered on peripheral parts of concentrations.

If it is impossible to find dispersed concentrations in the region under survey, the determination of the acoustic section of commercial concentrations is done with the help of an extended transducer lowered to the depth of item habitation or fixed in the section of a trawl adjacent to the cod-end and connected to the acoustic instrument by sonde cable.[11] In the last case, the acoustic section of items forming dense concentrations is determined from formula (6.5). The value of the density ρ_v is calculated as a ratio of the catch to the controlled filtered volume of the water.

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* It should, however, be taken into consideration that the values of acoustic sections at night can noticeably differ from those that take place during the day because of the variation of the orientation of fish.

THROUGH CALIBRATION

Through calibration is applied only when there is an absence of enough precise data on the acoustic section of items forming concentrations, and it is impossible to carry out their measurement *in situ*. In conducting the through calibration by commercial concentrations, their density is determined by one of the following methods: creating artificial concentrations in a net cage, the counting of items with their resolving registration by echo sounder, the use of means of underwater observation, or the use of trawls. Knowing the value of the density of a concentration, it is possible to calculate the general constant of calibration of the acoustic equipment with the integrator readings. The through calibration is rougher than the step-by-step one.

The creation of a concentration in a net cage is very laborious method, so it is used extremely rare; it can be applied only with small fish which can survive the trauma of being caught, loaded into a net cage, and adaptation to shallow depths.[12]

Calibration is possible if a target is multiple but the concentration density ρ_v is lower than the threshold, when multiple sound scattering occurs (see Section 1.3)

$$\frac{10}{\pi R^2 c\tau/2} < \rho_v < \frac{1}{c\tau L_{fish}^2} \qquad (6.16)$$

where R is the radius of a cage and L_{fish} is the average dimension of fish in a cage.

The calculation from formula (6.16) shows that, for example, with R = 1.0 m and L_{fish} = 10 cm, regarding low-frequency echo sounders with τ = 1.0 ms, the density may be within the limits from 4.0 to 66 sp/m^3, while in regard to high-frequency echo sounders with τ = 0.1 ms, from 40 to 660 sp/m^3.

Counting of individual items is possible with the resolving registration of comparatively large fish by an acoustic instrument. In this case, the density of a concentration, echo signals from that are integrated, is found by the division of the number of items counted by the value of the detection zone of an acoustic instrument. The limiting concentration density, with which items are registered separately, is tentatively calculated from the following formula:

$$\rho_v = \frac{1}{V_{imp}} = \frac{8}{\pi c\tau r^2 \theta_{eff}^2} \qquad (6.17)$$

If items are registered all together, a narrower beam instrument is used to calibrate an echo sounder. It is possible to carry out the calibration with an additional extended transducer connected to a sounder.

Use of means of underwater observation is possible only in the case when items under study are not frightened. The density of a concentration is determined with the help of photography, from an underwater apparatus or with television.

Photography can be used only in the case of a dense enough concentration. The average density of a concentration for a certain period is found by dividing the number of fish in a photograph by the total volume viewed by the camera for this period.[13]

Calibration through visual observations became possible with the use of underwater television in fisheries investigation. It is expedient to apply this method to comparatively uniform bottom concentrations of low density. The density of a bottom concentration is estimated proceeding from the ratio of the number of fish counted during a certain period of time to the value of the volume viewed.

Use of trawls allows one to tentatively estimate the density of concentrations if data on catching ability of a trawl are available. The area of the trawl mouth and the time of trawling determine the volume trawled. The catch and the coefficient of catching ability determine the number of items. Dividing the number of items by the volume trawled, it is possible to calculate the density of a concentration.

A more precise calibration of the equipment can be accomplished with the help of an extended device, fixed in the section of a trawl adjacent to the cod-end. In this case, in order to determine the density of a concentration of items passing through the area controlled by the acoustic device section of the trawl adjacent to the cod-end, it is not necessary to know the coefficient of catching ability.

INTERCALIBRATION

To verify the correctness of the calibration of the equipment installed on several vessels, the area with a comparatively extensive and uniform distribution of items under study is chosen in the region of operation. The vessels, on which the calibrated equipment is installed, move at the minimal distances required to exclude the mutual impact of disturbances occurring as a result of operating acoustic instruments and wake currents.

The readings of the integrators installed on the several vessels are radioed to a head vessel for the following treatment of the intercalibration data. The vessel, on which the maximal precision of equipment calibration is ensured, is chosen as the head. The density of registered concentrations is calculated, and the graphs of the equations of regressions are plotted. The calculation is made by the following formulas[8]:

$$\rho' = a_1\rho + a_2$$

$$\rho = b_1\rho' + b_2 \tag{6.18}$$

where ρ and ρ' are the values of area density received by the head and by the other vessels, respectively; a_1 and b_1 are the coefficients of regression, determined by the standard methods; and a_2 and b_2 are the constants in the equations of regressions.

In treating the intercalibration data, usually, only the graph of first equation (6.18) is plotted. The coefficient of correlation of density values, obtained by the head and by the other vessels, is then calculated:

$$K_{cor} = \sqrt{a_1 b_1} \tag{6.19}$$

If the coefficient of correlation $K_{cor} > 0.8$, the precision of the calibration of the equipment is considered satisfactory; if $K_{cor} < 0.8$, the calibration needs to be accomplished more precisely.

6.3 QUANTITATIVE INTERPRETATION OF COMMERCIAL RECORDINGS BY ECHO SOUNDER

It has already been mentioned in Section 6.1 that, because of several technical reasons, for the quantitative estimation of commercial concentrations, only vertically operating acoustic instruments (echo sounders) of various types are used at present. Norwegian scientific echo sounders of the type EK of the firm Simrad are the most widely used.[14] A great number of scientific vessels are equipped with them.

The most up-to-date Simrad system is a high-performance echo sounder for echo integration, split-beam target strength measurements, and analysis and reporting. The new electronic hardware is combined with up-to-date personal computer processing and a Windows operating system. The system provides facilities for accurate echo sounding, data storage, data analysis, and reporting of results. The instrument is designed for fish abundance estimation, fish behavior and species studies, and mapping of krill and plankton.

The use of the latest achievements in computer technology allowed Simrad to create highly efficient systems of marine biomass estimation, automating the process of collection and treatment of data received during acoustic surveys. The computer software is completely responsible for the treatment of data. Relations for equipment calibration, calculation of fish target strength and volume and area density of commercial concentrations, received on the base of the main sonar equation, are used as algorithms of the software (see Section 6.1).

An echo sounder control is accomplished through the computer keyboard. The system allows storing data for a following complete treatment. Characteristics of the transmitter and receiver are stable, the TVG laws regarding individual and multiple targets are precise, and the dynamic range for connecting integrators is wide. It foresees the connection of devices of signal treatment to calibrated outputs with different TVG laws. This makes it possible to simultaneously carry out the integration and measuring of target strength of commercial items. The computer display reflects echograms of fish concentrations and the bottom; it is possible to print tables of the multilayer distribution of volume and area backscatters, as well as the density of commercial concentrations.

The dynamic range of the receiver is more than 150 dB. Saturation resulting in underestimation never occurs with this echo sounder system. The combination of very low self-noise and unlimited TVG ensures correct measurement of all targets, from plankton to dense schools of fish. The sounder can operate eight frequencies simultaneously for comparison of fish reflectivity in the frequency range 18 to 200 kHz. Various types of processed data and complex sample data can be stored on the hard disk of the control processor.

The split-beam principle is used to find the position of individual targets in the transducer beam, to compensate the beam pattern, and to calculate corrected target strength values. The postprocessing software is intended for typical survey applications like assigning biomass to fish species, comparing results from different frequencies, storing results, and printing survey reports. Investigations can be performed in a virtually unlimited number of layers and regions. Integration of echo levels is performed in surface or bottom-locked layers, with an individual parameter setting for each layer.

All transducers used in the system are of high quality and are consistent. The transducers have been designed for fishery research using the very latest composite ceramics technology. The transducers ensure a split-beam transmission and reception and provide a frequency range from 18 to 200 kHz. With the low self-noise, high transmit power, efficient transducer and signal processing the system has outstanding detection capabilities. As shown in Section 2.1, at an operating frequency of 38 kHz, echoes from single fish (TS = –26.0 dB) can be observed at the depth of 1000 meters. Bottom echoes may be detected down to 9000 m depths with an 18 kHz operating frequency.

The Japanese firm, Furuno, produces another system.[15] It includes, besides ordinary echo sounder blocks, the integrator with the mounted inside the complex of measuring equipment for the calibration, the printer with the perforator, and the device for echo recording. The multichannel integration, the installed parameters of the equipment, the value of the volume backscatter, and the graph of the distribution of the concentration density by depth are printed on the echogram. The possibility of quantitative estimation of schools is foreseen. For this purpose, the microprocessor calculates the cross section of schools. With these data, it is possible to calculate the biomass of a school by the average value of target strength and mass of individual specimens.

ESTIMATION OF CONCENTRATION DENSITY

It has been shown in Section 6.1 that the density of a concentration consisting of one species, averaged for all lengths, is determined from the following formula:

$$\rho_s = CM_1 \tag{6.20}$$

where C is the value of the scale of an integrator and M_1 is the integrator reading for one ping.

For practical purposes, it is more convenient to express this formula as:

$$\rho_s = \frac{CMv_{vess}}{60lf_{imp}} \tag{6.21}$$

where M is the integrator reading for a certain interval of the path of a vessel, v_{vess} is the speed of a vessel movement, l is the unit of a sampling distance, and f_{imp} is the ping rate frequency, corresponding to the range chosen for an instrument.

For quantitative estimating of a concentration according to length (weight) groups, area densities of a concentration of items of each group are found. The calculation is made from the following formula:[8]

$$\rho_j = \frac{K_j}{\sum_{j=1}^{n}\left(K_j / C_j\right)} \frac{M v_{vess}}{60\, l f_{imp}} \tag{6.22}$$

where C_j is the value of the scale of an integrator regarding items of a given length (weight) group, K_j is the percentage of the weight content of a length (weight) group in a concentration, and n is the number of groups.

It follows from expressions (6.21) and (6.22) that for reliable determination of the area concentration density, it is necessary to know the following parameters: the value of the scale of an integrator regarding each length (weight) group C_j, the unit of a sampling distance l, the speed of vessel movement v_{vess}, the ping rate frequency f_{imp}, the readings of an integrator M, and the percentage of the weight content of a length (weight) group in a concentration K_j. The use of expression (6.22) is also necessary in carrying out acoustic surveys of stocks of various fish species, as well as of different generations of fish.

The percentage content of a species or weight group in a concentration is determined from the results of control fishing. In order to ensure that such a determination will be close to the real content of concentrations under study, it is important to take into account the difference in the catching ability of a trawl regarding various species or dimensions of commercial items. However, the determination of the differential coefficient of catching ability is quite difficult and not always accomplishable. Some success has been achieved in determining the differential coefficient of catching ability of trawls on concentrations of bottom fish with the help of underwater apparatus.[16]

PELAGIC CONCENTRATIONS

The main condition for a reliable quantitative estimation of commercial pelagic concentrations is the energetic range of acoustic instruments required for their detection. Modern acoustic instruments reliably detect pelagic concentrations at comparatively small depths of habitation; it is natural that, in this case, there is no problem with their quantitative estimation. It is another matter when commercial items remain at significant depths and are registered by the equipment against a background of disturbances. Disturbances can be especially great when working in bad weather conditions. The decrease of the level of disturbances is achieved by an appropriate choice of the course and speed of the vessel motion.

With small disturbances, the separation of useful signals is accomplished with the help of the threshold device of an integrator, which allows for controlling the minimal level of registration of signals. If items under study are registered against a background of great noises or echo signals from sound-scattering layers, then integrator readings should be corrected taking into account the contribution of disturbances. The latter is usually estimated through the second channel of an integrator, which is set on the depth where noises are registered but items under survey are absent. A comparison of the readings of the two channels provides a possibility of estimating weak echo signals from concentrations even though they are lower than the level of noises. As has been shown in Section 1.5, the process of selecting useful signals against a background of disturbances can be automated.

SURFACE AND BOTTOM CONCENTRATIONS

Significant difficulties in detection and quantitative estimation arise when operating on surface and bottom commercial concentrations. Such concentrations are only partially registered by fish-finding instruments because of various limiting factors (see Section 4.2). An estimation of such concentrations can be accomplished by the combination of the acoustic method with the trawling one. In this case, the part of a concentration, which is remote from the surface or bottom of a sea, is estimated by an acoustic method exactly as pelagic concentrations are. Surface or bottom areas, in which items are poorly detected or completely undetected, are surveyed by controlled trawling.

Area concentration density as a result of trawling (in tons/mile^2) is found from the following relation:[17]

$$\rho_{\text{int}} = \frac{3.4 \times 10^6 Q L_{\text{vert}}}{K_Q W_{\text{trawl}}} \tag{6.23}$$

where Q is the mass of catch for an hour of trawling, tons/hour; K_Q is the coefficient of catching ability of a trawl (see Section 8.1); L_{vert} is the vertical opening of a trawl, m; and W_{trawl} is the technical productivity of a trawl, m^3/hour.

Summarizing densities, received in the trawled and integrated layers, allows one to tentatively estimate the area concentration density.

Dividing expression (6.23) by formula (6.20), we obtain the coefficient of masking

$$K_M = \frac{3.4 \times 10^6 Q L_{\text{vert}}}{K_Q W_{\text{trawl}} C M_1} \tag{6.24}$$

The character of the relief and the distribution of unevenness in various areas may be different; therefore, the degree of masking of bottom fish readings is not always the same. Taking this into account, carrying out controlled trawling and determination of the coefficient of masking from formula (6.24) is often required.

When the coefficient of masking is known, it is possible to introduce corrections in calculating the density of concentration sections located near the bottom. Densities of concentration areas, registered in the water column and not subjected to masking, are determined, as are densities of pelagic concentration.

Summing up all of the above-mentioned, it is possible to conclude that the methods considered allow for estimating the density of surface, pelagic and bottom concentrations with different degrees of accuracy. Regarding pelagic concentrations, which are reliably registered by acoustic instruments, the accuracy of determining the density depends, first of all, upon the error of estimating the target strength of individual items. As a result of a detailed analysis carried out in 1982, we established that, in respect to one species concentration of items of one size, the error of the concentration density varies within the limits ±50%.[9] However, the up-to-date practice of acoustic works shows that, due to the more sophisticated technique and methods of measurements, the error of acoustic estimation of the density of fish concentrations within a water column, under favorable conditions, is usually less than 20–30%.

In the case of complicated measurements of surface and bottom concentrations, the accuracy of determining the density may be considerably lower. Such measurements are very expensive, as they require a significant amount of the expedition time. Therefore, for the practical realization of accurate enough measurements of the density of concentrations near the surface and bottom, new methodological and technical solutions are required.

6.4 QUANTITATIVE INTERPRETATION OF COMMERCIAL RECORDINGS BY SONAR

It has been mentioned in a previous section of the chapter that, at the present time, echo sounders are widely applied for quantitative estimation of commercial concentrations. However, in some cases, the use of an echo sounder does not allow one to receive correct estimates of the density of concentrations under survey. In particular, in estimating surface concentrations of mobile fish, which are strongly frightened by a vessel, underestimated values of the density and quantity of fish are often received. The problem is that echo sounders possess only a narrow detection range outside a vessel's boundaries; therefore, when fish are frightened, they fall only partially into the detection zone of an instrument, which results in an underestimation of concentrations.

The phenomenon of fish frightening in surface water layers is observed in seas, as well as in internal waters. Horse mackerel, scomber, herring, and other pelagic fish are strongly frightened. Bottom fish (cod, sea perch, whiting, and other species) are not so frightened. It is typical that permanent work of a powerful fisheries fleet in commercial regions does not lead to adaptation; on the contrary, it intensifies fish reaction to a vessel noise.

Vessel noises frighten fish keeping dispersedly, in schools or concentrations. With a schooled distribution, fish react especially sensitively. Underwater observations by application of various technical means show that schools of many species of pelagic fish, at depths of 50 m and deeper, distinctly react to a vessel noise. Fish move away from a vessel from the depths of 100–150 m and sometimes even deeper. As a vessel approaches, the speed of fish motion increases; the density of fish concentrations measured by instruments usually decreases greatly. For example, according to the results of observing schools of herring at depths of 30–60 m, when a vessel passed over the fish, the density of their concentrations fell some 70–80% on the average.[18]

In estimating surface concentrations of easily frightened fish, it is expedient to apply sonar, which allows for registering commercial items far away from a vessel. Unfortunately, until now, sonar has not been used for quantitative estimation because of a number of methodological and technical difficulties. Determining the kilometric sound attenuation, the path of the ultrasonic beam of an instrument, the location of schools with regard to the beam, the necessity of accounting for the variability of the acoustic sections of commercial items, and the integral directivity factor are among these problems.

It will be possible to overcome the cited difficulties only after considerable improvements in the acoustic technique and methods of treating the information used. Substantial progress in this direction has already been made. The application of computer technology in fish-finding equipment and the creation of various scanning sonars allows for determining a way of resolving the problem of the quantitative estimation of commercial concentrations with the help of an acoustic instrument operating horizontally.

The Simrad firm has made attempts at quantitative estimation of schools with scanning sonar used as indicators of underwater conditions.[19,20] For this purpose, the microprocessor treatment of sonar echo signals is executed inside a "window" set on the display according to range and angle corresponding to the dimensions of a registered school. The computer performs a number of operations on echo signals from a school within the limit of the chosen window, including squaring, integration, and multiplication by the volume of a school. The calculated value, proportional to the biomass, is indicated on the display in relative units. This allows a fisherman to make a relative estimation and to choose the most convenient school, taking into account its commercial significance. However, such a quantitative estimation of schools may only be tentative so far. For receiving a more precise estimate, as mentioned above, it is necessary to take into account the target strength of fish, the aspect of their insonification, and other characteristics.

Vertical scanning of an ultrasonic sonar beam perpendicularly to the direction of motion, from the starboard or port side of a vessel, seems to be rather applicable for a quantitative estimation. Such a traverse mode of acoustic investigation allows for excluding the variation of the distance to fish concentrations in the direction of vessel motion and permits receiving the clear view of their distribution and dimensions on the indicator. As an indicator of the behavior of fish, as well as the direction and speed of their movement, it is possible to use plane tables of underwater conditions. Knowledge of the direction of fish motion provides the possibility of determining their orientation relative to the ultrasonic sonar beam, and to take this into account when estimating acoustic characteristics.

Further considerations about the application of sonar for a quantitative estimation will be, first of all, related to the school distribution of concentrations located in surface layers of the ocean, as easily frightened fish usually form compact movable schools. For the sake of simplicity of the following calculations, let us consider the path of the ultrasonic beam as being rectilinear, i.e., without accounting for the refraction of the beam because of the nonuniform structure of the sea; the angle of inclination of the sector of ultrasonic beam will be taken equal to $\beta = \theta/2$. The width of the sector of scanning is chosen so that fish fall into the detection zone from all depths of their distribution. The location of the sector of ultrasonic beam and fish schools under the traverse mode of sonar operation is shown schematically in Figure 6.3.

It follows from the figure that, regarding the vertical location with the corresponding TVG law, expression (6.8) for determining the area concentration density (in tons/mile^2) can be presented as

$$\rho_s = \frac{3.4\,wM_1h}{C_{ea}\,\Psi\, r_{int}\,\sigma} \tag{6.25}$$

where h is the average thickness of the water layer, in which fish are registered, m; and r_{int} is the range of integration, m.

In this case,

$$h = r_{aver}\theta$$

$$r_{aver} = (r_{max}+r_{min})/2;\ r_{int} = r_{max}-r_{min} \tag{6.26}$$

$$\theta = n_{beam}\theta_{beam};\ \Psi = n_{beam}\Psi_{beam}$$

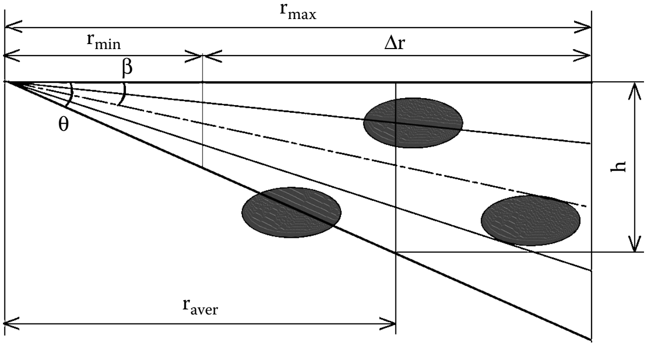

FIGURE 6.3 Scheme of locating the scanning sector and fish schools with the transversal investigation by sonar.

where r_{min}, r_{aver}, and r_{max} are the minimal, average, and maximal distances, respectively, m; θ and θ_{beam} are the width of the sector and elementary beam, rad; n_{beam} is the number of elementary beams in the sector; and Ψ_{beam} is the integral directivity factor of the elementary beam.

Substituting expression (6.26) into formula (6.25), we obtain the following relations:

$$\rho_s = \frac{1.7\,M_1 w\,\theta_{beam}\left(r_{max}+r_{min}\right)}{C_{ea}\,\Psi_{beam}\left(r_{max}-r_{min}\right)\sigma} = CM\,\frac{r_{max}+r_{min}}{r_{max}-r_{min}} \tag{6.27}$$

where C is the value of the scale of an integrator.

To estimate the density of commercial concentrations from formula (6.27), it is necessary to take into account the peculiarities of determining the TVG law and the acoustic section of fish situated on a horizontally located transducer axis.

For determining the acoustic section of fish situated on the axis of the ultrasonic beam, it is necessary to know the space indicatrix of the sound backscattering by the fish and its orientation angle. The angle of orientation of fish relative to the acoustic axis is found from the readings on the plane table of underwater conditions, on the screen of which the direction of fish movement is fixed. The indicatrixes of the sound backscattering by fish are measured under stationary conditions.

It should be noted that mainly plane indicatrixes of the sound backscattering have been measured until now under stationary conditions; information on regularities of the space sound scattering is scant. It is necessary to fill this gap and to carry out the required volume of measurements of the space indicatrixes regarding all the main species of commercial fish of various lengths.

The results of our measurements of the space indicatrix of the sound backscattering by commercial fish are given as example in Figure 1.6 (see Section 1.2). It is easy to understand from the figure that, with the horizontal location of schools, in which fish are oriented in a certain direction, their acoustic sections on the axis of the ultrasonic beam of an instrument can be determined from the space indicatrix of scattering by the known inclination angle β and the azimuth angle φ.[*] The knowledge of space indicatrixes also allows calculation of more accurate values of the integral directivity factor taking into account the sound backscattering by fish.

In estimating the density of concentrations with sonar, it is important to exclude the impact of the distance to fish and the kilometric attenuation of the sound in the water on the values of echo signals. For this purpose, it is necessary to use the TVG, the law of variation in which can be controlled within great limits. The changes in the TVG law are determined, first of all, by the peculiarities of the sound attenuation in surface layers of the ocean. Depending on the saturation of surface layers with air bubbles and other heterogeneities of the medium, the sound attenuation at various distances can vary strongly.

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[*] Regarding concentrations, in which specimens are distributed irregularly, the determination of the acoustic section of items is connected to the averaging of values by all azimuth angles for a given inclination angle.

The determination of the sound attenuation in surface layers of the ocean cannot be calculated on the basis of any theoretical relations; therefore, experimental measurements under real conditions are required. The averaged variations of the sound attenuation by depth, obtained with the help of the measuring equipment operating on the principle of the "autocirculation method," are given in Figure 6.4.[21–23] It is possible to reduce the values of the sound attenuation from the distances used in the experiments to real ranges of sonar. The scales of distances obtained from the results of such calculations are given in the figure by the abscissa axis. Obtaining dependences of sound attenuation on the distance in the region of operation makes it possible, in investigating surface layers of the ocean, to introduce required corrections into the TVG law of the sonar receiver.

The solution of problems connected to the determination of the TVG law and of the fish acoustic section on the sonar transducer axis allows for accomplishing complete calibration of the equipment and calculating the value of the scale of an

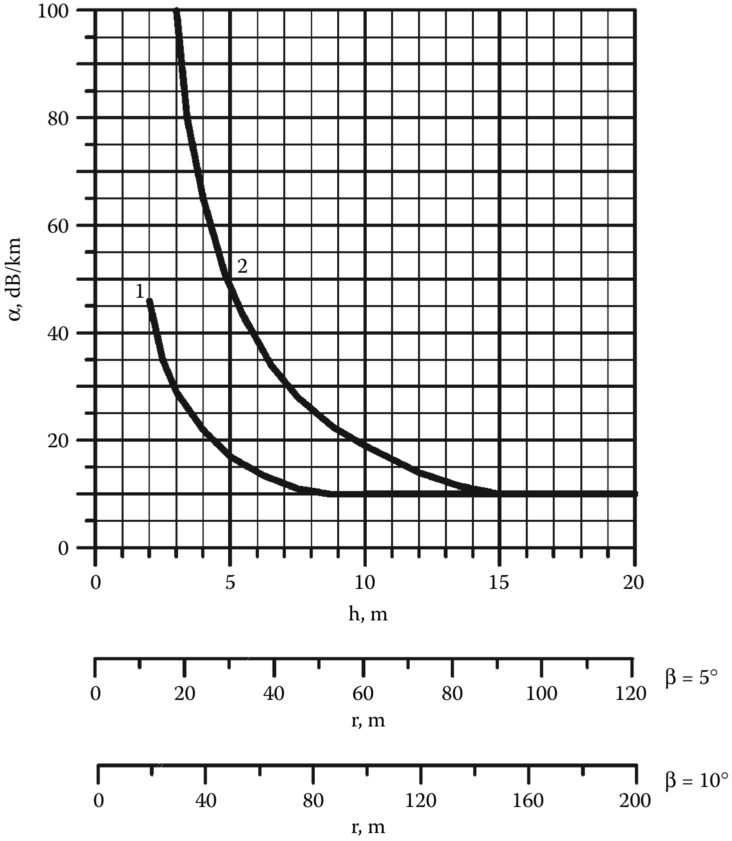

FIGURE 6.4 Dependence of the sound attenuation by sonar on the distance with a frequency of 30 kHz, the acoustic beam inclination angles of $\beta = 5°$, $\beta = 10°$ and various roughnesses of the sea: 1, wave height 3.5–4.0 feet; 2, wave height 8.0–12.0 feet.

integrator. After that, as follows from formula (6.27), it is necessary to install the range of integrating echo signals from fish by distance in order to determine the density of concentrations.

In carrying out acoustic surveys, the widest range of integration distances should be used; as the wider the range, the greater is the area of a zone investigated by sonar. This is especially important with a nonuniform fish distribution by water area. In this case, for ensuring accurate enough estimation of concentrations, a more detailed investigation of the region is required. The distances, within the limit of which the reliable registration of fish concentrations is observed, determine the choice of the range of integration. The minimal border of the range of integration r_{min} is set at the distance where a vessel does not frighten fish; the maximal one r_{max} corresponds to the limiting detection distance.

Summing up all the above-mentioned, we think that the suggested method of estimating the density of concentrations of easily frightened fish with the help of special scanning sonar gives the possibility of carrying out acoustic surveys with an accuracy admissible for the practice. Currently, the various models of such acoustic complexes are under elaboration.

As, so far, there are no special complexes for determining the density of concentrations of easily frightened fish, we suggest estimating them roughly with the use of existing sonar. In this case, taking the value ρ_s, calculated for sonar from formula (6.25) as the real concentration density and, in comparing it with the value of density obtained with an echo sounder, the correction coefficient $K_{correct}$ is received. With the help of this coefficient, it is possible to correct the results of acoustic surveys taking into account the frightening of fish by a vessel; i.e.,

$$K_{correct} = \frac{\rho_{sonar}}{\rho_{sounder}} = \frac{C_{sonar} M_{sonar}}{C_{sounder} M_{sounder}} \frac{\theta\left(r_{max} + r_{min}\right)}{2\left(r_{max} - r_{min}\right)} \tag{6.28}$$

where M_{sonar}, C_{sonar}, and ρ_{sonar} are the average readings of the integrator, the value of its scale, and the area concentration density, respectively obtained with the use of sonar; and $M_{sounder}$, $C_{sounder}$, and, $_{sounder}$ are the same with the use of an echo sounder.

The coefficient of correction is an objective characteristic of a frightening property of commercial fish; it can be measured with the help of sonar, an echo sounder, and an integrator of any type appropriate for such measurements.

It follows from relation (6.28) that, prior to determining the coefficient $K_{correct}$, the measurements of the constants C_{sonar} and $C_{sounder}$ should take place; i.e., the calibration of the equipment. Special attention should be paid to the estimation of the fish acoustic section, the value of which strongly depends upon the direction of insonification.

With the irregular fish location, which is usually observed in concentrations, the value of the average acoustic section (σ) can be obtained from the polar diagram of the sound backscattering by fish through the averaging of values by all directions (Figure 6.5). To determine the average acoustic section in schools, where specimens are located regularly, it is first necessary to establish the direction of their motion with sonar. Only after that, knowing the location of fish relative to the beam of sonar, is it possible to determine the average acoustic section from the diagram of backscattering within the width of the characteristic of the transducer of an instrument.

Having calculated the constants regarding sonar (C_{sonar}) and an echo sounder ($C_{sounder}$), it is possible to start determining the coefficient of correction $K_{correct}$. For this purpose, the measurements of readings of the integrators connected to sonar (M_{sonar}) and the echo sounder ($M_{sounder}$) are conducted. For accomplishing the mentioned measurements, the area of commercial concentration with a comparatively uniform fish distribution is chosen. To exclude the influence of area reverberation and the sound attenuation because of the water aeration, it is expedient to carry out all the measurements in calm weather. Readings of the integrators, working with an echo sounder and sonar, are taken on the same concentrations and at the same vessel speeds that will be used in the acoustic surveys.

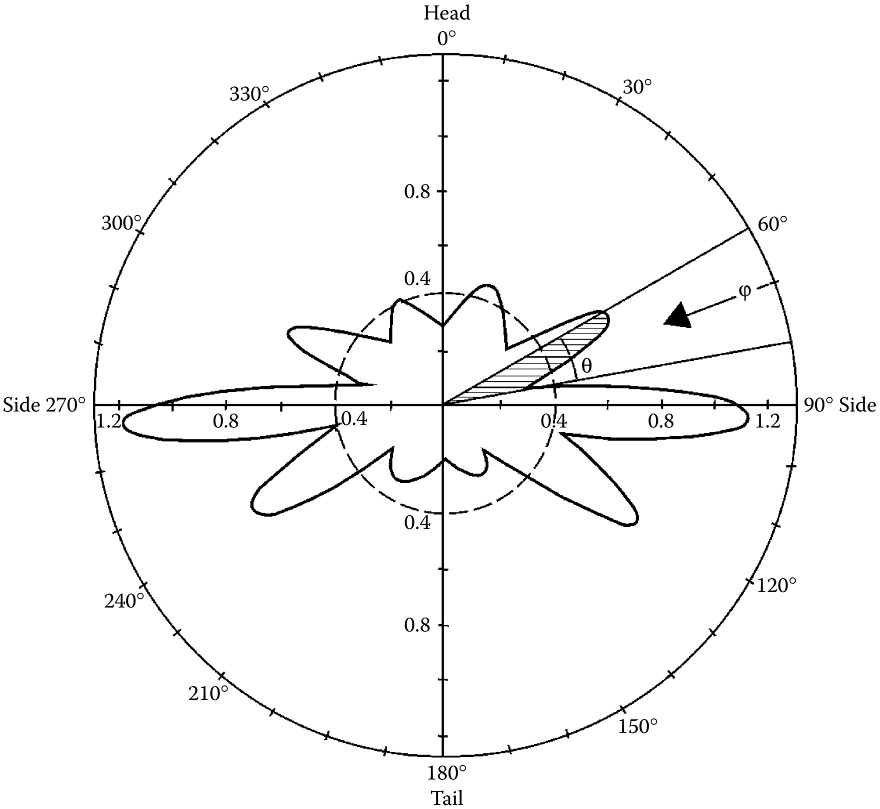

FIGURE 6.5 Polar diagram of sound backscattering by fish 33 cm long with a frequency f = 20 kHz.

To clearly understand the procedure of determining the degree of influence of the frightening of commercial concentrations on the estimation of their biomass, let us consider an example of calculating the coefficient $K_{correct}$ regarding schools of horse mackerel in the southeastern part of the Pacific Ocean, located in the upper water layers.

A typical acoustic station is used to measure the coefficient $K_{correct}$. Both the vertical and horizontal tracts of the station operate alternately. Regarding the parameters, identical for both tracts, it is possible to find their constant. Let $C_{ea} = 2.8 \times 10^6$. The effective transducer directivity angle $\theta = 20^\circ$ (0.35 rad); the integral directivity factor $\Psi = 3.5 \times 10^{-2}$.

The average length of horse mackerel $L_{fish} = 33$ cm, its weight w = 350 g. The acoustic section of horse mackerel with the vertical location $\sigma = 50\ \text{cm}^2$ (according to the data of *in situ* measurements). The angle of insonification of fish, measured with sonar, $\theta = 70^\circ$. The average acoustic section of horse mackerel regarding schools, determined from the polar diagram of the backscattering with $\theta = 70^\circ$ within the sector of $\phi = 20^\circ$ is equal to $\sigma = 0.5 \times 50 = 25\ \text{cm}^2$; the same with irregular fish orientation, observed in concentrations, $\sigma = 0.4 \times 50 = 20\ \text{cm}^2$ (Figure 6.5).

The general constant is calculated from formula (6.13): using an echo sounder $C_{sounder} = 31\ \text{tons/mile}^2$; applying sonar $C_{sonar} = 62\ \text{tons/mile}^2$.

The measurements of horse mackerel schools were accomplished during a period when a wave height was 1.5–2.0 feet when the vessel speed $v_{vess} = 9.0$ knots. With a horizontal location, the beam is directed perpendicularly to the course of a vessel; the inclination angle 10°. The borders of integration with the horizontal location were $r_{min} = 200$ m, $r_{max} = 500$ m. The unit of sampling distance was l = 3.0 miles. The reading of an integrator was with the horizontal location, $M_{sonar} = 9850$; with the vertical one, $M_{sounder} = 2520$. From formula (6.21), after reducing to one ping: $M_{sonar} = 7.71$ and $M_{sounder} = 1.97$.

The tentative value of the coefficient of correction, calculated from formula (6.28), is equal to

$$K_{correct} = \frac{62 \times 7.71}{31 \times 1.97} \times \frac{0.35(500 + 200)}{2(500 - 200)} = 3.2$$

This means that, because of the fish frightening, the concentration density of horse mackerel schools determined with an echo sounder appeared to be 3.2 times less than the true one.

It has already been mentioned that the extent of fish frightening depends on the character of their distribution and can substantially vary in time, including in the course of their daily vertical migrations. Therefore, it is necessary to determine the values $K_{correct}$ regarding each species of fish under various distributions and behaviors, gradually accumulating the required bank of data. Further on, such a bank of data will allow for avoiding laborious measurements of the coefficient $K_{correct}$ in the practice of carrying out surveys of easily frightened fish.

REFERENCES

1. Yudanov, K.I., Possibilities of estimating fish concentrations density by acoustic instrument data, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), Fish behavior and "fisheries prospection," Ijevsky, G.K., and Manteifel, B.P., Eds., 36, 250, 1958 (in Russian).
2. Kalikhman, I.L., Tesler, W.D., and Yudanov, K.I., Methods of determining the density of fish concentrations, in Meeting on Hydroacoustical Methods for the Estimation of Marine Fish Populations, 25–29 June 1979, II: Contributed Papers, Discussions, and Comments, Suomala, J.B., Ed., The Charles Stark Draper Laboratory, Cambridge, MA, 533, 1981.
3. Kalikhman, I.L. and Tesler, W.D., The effective parameters of the real acoustic beam, in Selected Scientific Papers of the ICES/FAO Symposium on Fisheries Acoustics, Bergen, Norway, 21–24 June 1982, Nakken, O., Venema, S.C., Eds., FAO, Rome, 9, 1983.
4. Johannesson, K.A. and Mitson, R.B., *Fisheries Acoustics. A Practical Manual for Aquatic Biomass Estimation*, FAO Fisheries Technical Paper 240, FAO, Rome, 249, 1983.
5. Kieser, R. and Mulligan, T.J., Analysis of echo counting data: A model, *Canadian Journal of Fisheries and Aquatic Sciences*, 41(3), 451, 1984.
6. Kalikhman, I.L., Tesler, W.D., and Yudanov, K.I., Methods of calibrating hydroacoustic instruments, in Meeting on Hydroacoustical Methods for the Estimation of Marine Fish Populations, 25–29 June 1979, II: Contributed Papers, Discussions, and Comments, Suomala, J.B., Ed., The Charles Stark Draper Laboratory, Cambridge, MA, 259, 1981.
7. Foote, K.G., Knudsen, H.P., Vestnes, G., McLennan, D.N., and Simmonds, E.J., Calibration of acoustic instruments for fish density estimation: A practical guide, *ICES Cooperative Research Report*, 144, 69, 1987.
8. Yudanov, K. I., Kalikhman, I. L., and Tesler, W. D., *Manual of Acoustic Surveys*, VNIRO, Moscow, 124, 1984 (in Russian).
9. Kalikhman, I.L., Estimating the accuracy of the determination of fish concentration density by acoustic method, in Proceedings of the Institute of Biology of Inland Waters, Estimating Errors of Hydroacoustical and Ichthyological Investigations, Academy of Science of the USSR, *Rybinsk*, 49(52), 103, 1982 (in Russian).
10. Tesler, W.D., A simplified calculation of the effective parameters of the acoustic beam in echo surveys, *Fisheries*, 2, 61, 1981 (in Russian).
11. Artemov, A.T., Determination of the acoustic backscatter cross section of small pelagic organisms in aggregations, *Oceanology*, 23(2), 264, 1983 (translated from Russian).
12. Johannesson, K.A. and Vilchez, R., Application and some results of echo integration methods in monitoring Peruvian anchovy resources, in Meeting on Hydroacoustical Methods for the Estimation of Marine Fish Populations, 25–29 June 1979, II: Contributed Papers, Discussions, and Comments, Suomala, J.B., Ed., The Charles Stark Draper Laboratory, Cambridge, MA, 765, 1981.
13. Ermolchev, V.A. and Zaferman, M.I., Results of experiments on the video-acoustic estimation of fish target-strength *in situ*, in Acoustics in Fisheries and Aquatic Ecology. Part 1, Proceedings of an ICES Symposium Held in Montpellier, France, 10–14 June 2002, MacLennan, D.N., Ed., *ICES Journal of Marine Science*, 60(3), 544, 2003.

14. Anon., *EK60 Scientific Sounder System, A New Generation Scientific Fishery Research Tool*, Simrad, A Kongsberg Company, Simrad Marketing, Horten, Norway, 2002.
15. Ohshimo, S., Acoustic estimation of biomass and school character of anchovy *Engraulis japonicus* in the East China Sea and the Yellow Sea, *Fisheries Science*, Tokyo, vol. 62(3), 344, 1996.
16. Zaferman, M.L. and Serebrov, L.I., Methods and results of the study of the cathability of trawls. Investigations on the optimization of fisheries and development of fishing gears. VNIRO, Moscow, 84, 1985 (in Russian).
17. Treschov, A.I., *The Intensity of Fisheries*, Pischepromizdat, Moscow, 180, 1983 (in Russian).
18. Olsen, K., Fish behaviour and acoustic sampling, in Developments in Fisheries Acoustics. A Symposium Held in Seattle, 22–26 June 1987, Karp, W.A., Ed., *Rapports et Proces-Verbaux des Reunions*, 189, 147, 1990.
19. Bodholt, H., A multibeam sonar with colour display, Electronics for Ocean Technology, Institution of Electronic and Radio Engineers, London (UK), 283–290, Book Monograph. *Proceedings of the Institution of Electronic and Radio Engineers*, 51, 1981.
20. Mizund, O.A. and Coetzee, J., Recording fish schools by multi-beam sonar: Potential for validation and supplementing echo integration recording of schooling fish, *Fisheries Research*, 47(2–3), 149, 2000.
21. Borisenko E.S., Bondarenko, V.M., Stefanov, S.R., and Chistoserdov, Yu.P., The investigation of sound attenuation in the sub-surface layer of the ocean by the autocirculation method, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series "Fishery Acoustic Problems," Yudanov, K.I., Kalikhman, I.L., Shabalin, V.N., Eds., VNIRO, Moscow, 136, 1983 (in Russian).
22. Borisenko, E.S., Investigation of losses of the acoustic energy in water-fish medium, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series "Fishery Acoustic Problems," Yudanov, K.I., Kalikhman, I.L., Bondarenko, V.M., Eds., VNIRO, Moscow, 32, 1989 (in Russian).
23. Borisenko, E.S., Results of experimental measurements of the excessive sound attenuation in aerated layers of the ocean, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series "Fishery Acoustic Problems," Yudanov, K.I., Kalikhman, I.L., Bondarenko, V.M., Eds., VNIRO, Moscow, 40, 1989 (in Russian).

7 Acoustic Surveys of Commercial Resources

As mentioned earlier, an acoustic reconnaissance is understood as a complex of steps aimed at the search and detection, the quantitative and qualitative interpretation of commercial concentrations, as well as the estimation of their biomass. In the previous chapters, we have been analyzing in detail the possibilities of the search, detection, and interpretation of concentrations by acoustic instruments. In the present chapter, we will consider questions related to the estimation of the state of commercial stocks.

The necessity of the estimation of the state of biological resources has lately become especially urgent in connection with the decrease of the fish stocks in various regions. Because of the great technical power of a fisheries fleet, the exploitation of detected concentrations proceeds very quickly and often leads to an abrupt reduction in the stocks. With a poor state of the stocks and the heavy impact of numerous anthropogenic factors, which are observed nearly everywhere, small mistakes in forecasting the biological resources and commercial withdrawal may result in significant limitation and even prohibition of exploitation of the population. To preserve commercial resources from overexploitation and to ensure stable fishing, the well arranged monitoring of biological resources is required.

To estimate the state of the stocks by the acoustic method, an acoustic survey of the habitat of distribution of commercial items is carried out. The vessel conducts a series of transects within a fixed area; echo integrator (or counter) readings for a certain sampling distance along transects are taken; the average values of density within these areas are estimated; the density distribution in this area is plotted; and the value of the biomass is calculated and its error is estimated.

While conducting acoustic surveys of biological resources in various fisheries basins, not only the overall biomass of items is estimated, but also their differential quantities of age composition. The results of estimation of the distribution, quantity, and biomass, acquired on the basis of data from an acoustic survey, taking into account ages and maturity as well as biostatistic indices, allow researchers to make conclusions about the yield of various generations and to forecast the state of the stocks and the allowable catch.

A stable equilibrium of the ecological system of a region can be maintained by conducting surveys, controlling the state of biological resources and commercial withdrawal of the main species of fish as well as the other species making up the ecosystem. While estimating the biological resources, it is necessary to take into consideration the food interrelations of various species in order to determine the extent of influence of the competition, predation, and cannibalism in the rise or fall of their quantity.

Taking into account the close relationship of a distribution, quantity, and biomass of fish concentrations and their habitat conditions, surveys of biological resources and fishing conditions must be multidisciplinary. Later on, let us conventionally refer to multidisciplinary surveys as accounting ones.[1–3] They encompass, in addition to the collection of data on distribution, quantity, and biomass of commercial items, ichthyologic, oceanographic, and other measurements as well (see, for example, Reference 4).

The major role of some information and the extent of complexity of surveys are determined by the tasks of investigations. If the goal of the survey in a traditional area is the estimation of the quantity and biomass of the population according to the length and age composition, the major information is obtained with the help of acoustic surveys and control fishing, and oceanographic data are supplementary.

More detailed oceanographic information on the parameters of the water medium is needed in cases of anomalous conditions, when the distribution of fish strongly differs from normal. In those cases, more frequent oceanographic stations and transects should be conducted. When studying the impact of the environment on the distribution of fish, information on oceanographic parameters must be collected in even greater detail.

Data on distribution, quantity, and biomass of concentrations, acquired with the help of acoustic surveys, are tied up to oceanographic characteristics of the medium and physiological condition of fish and are compared with the forecasted stock for this period. If there is a significant difference in commercial resources from the forecast values, necessary steps are taken; for example, corrections to the forecast value of commercial withdrawal are introduced.

To arrange and carry out accounting surveys for studying the ecosystem interrelationships, a wide circle of questions connected to their design, collection, and treatment of ichthyologic, oceanographic, and other information must be answered. However, the above-mentioned questions have been poorly developed as of yet. It is necessary to elaborate and scientifically base the methods of the complex design of surveys and their strategy and tactics. These problems must be solved by joint efforts of experts in ichthyology, acoustics, and oceanography regarding specific regions and items of fishery.

The entire complex of the above-mentioned problems is considered in the present and the following chapters. The solutions to these problems in estimating, controlling, forecasting, and regulating fisheries resources with the help of accounting surveys are shown.

7.1 ACOUSTIC SURVEY TACTICS

An acoustic survey generates considerable expenses; therefore, it should be carefully planned and accomplished in accordance with the tasks set, which can significantly differ, depending upon the extent of mastery of a region under study and the survey conditions. *Tactics is a system of operations in designing and carrying out an acoustic survey ensuring the solution of its tasks.*

THE CHOICE OF THE SURVEY PERIODICITY

The survey periodicity depends on the state of the stocks of commercial items. It is usually enough to conduct rare surveys (once a year) to control the state of biological resources with a comparatively stable stock, as well as under extreme conditions, when fisheries are prohibited or the stock is poorly exploited because fisheries are not profitable during a certain period. More frequent surveys are necessary with an intensely harvested state of stocks or under anomalous natural conditions, when seasonal control is required.

To regularly control the state of the stock, surveys within the period of fattening are undertaken first. With an intensely fished state of the stock, when its value is close to critical, a regular control of the state of resources is especially important, as well as a corresponding, timely correction of commercial withdrawal. In this case, it is expedient to also estimate a spawning shoal. In fact, the general state of the stock of a population and its stability depend directly on the quantity of the spawning shoal. It is most convenient to carry out surveys of spawning grounds within the periods when the spawning process occurs within brief periods and all mature fish gather in one region.

It is more complicated to estimate a spawning shoal if the spawning process occurs step-by-step and lasts a long time. It is still harder to do it when a species consists of several populations, each of which has its own periods and places of spawning. In such cases, a survey of spawning resources is only possible when the spawning grounds and the dependences of the peculiarities of a spawning on the water medium conditions have been studied enough.

Knowledge of the quantity of the species studied by ages allows one to estimate the productivity of generations taking into account their commercial withdrawal. With an intensely harvested state of fisheries stock, to study the perspectives of its reinforcement at the expense of younger generations, the estimation of the quantity of fry is required. It is expedient to quantitatively estimate the earlier generations, including recruits entering the spawning shoal, in the course of the accounting survey of commercial stocks within the fattening period, when all of the age groups stick close together.

Owing to the numerous factors affecting the reliability of the results, a survey is preceded by careful preparation, during the course of which preliminary data on items, region, and water medium are collected. Instructions on fisheries, results of previous surveys and investigation voyages, hydrographic characteristics of the area, fishery data, etc., serve as sources of such information.

Based on information available, the dimensions of the region under investigation and the character of the distribution of concentrations by water area and by depth are estimated; the duration of the survey is fixed. The period of work is determined taking into account biological conditions and the behavior of items as well as weather conditions. To acquire reliable information on the state of the stock, surveys are carried out at the end of biological periods, when the majority of the population gathers in a specific region. At this time, fish keep comparatively stably, within a limited area, gathering in rather dense concentrations before migrating to places of wintering, fattening, or spawning. Surveys are conducted within the period of mass arrival of fish to the area of concentration. The time of mass fish arrival is estimated from retrospective data, so efforts of researchers are aimed at arrival to a survey location prior to the time of occurrence.

In the beginning, a short preliminary investigation is carried out to estimate the general conditions, the distribution, and habitat area of commercial items and to approximate values of their quantity. Besides the vertical distribution of items by area, vertical sections of the volume density are of considerable interest. The graphs of vertical sections are obtained by means of the multichannel integration of echo signals from various depths (Figure 7.1). Such graphs facilitate obtaining a more complete idea of the distribution of items in the region.

Only with anomalous natural conditions, when the limits and the character of distribution of commercial items change strongly, must researchers carry out an entire preliminary survey. While planning a preliminary survey, attempts at combining its transects with standard hydrological transects and stations are made, which ensure a more effective use of ship time and the collection of all required information. The length of transects and the distance between them is chosen based on the preliminary estimate of the area of distribution of items.

If a preliminary survey in a chosen region shows that mass fish arrival has not yet begun, a preliminary investigation is continued to receive more complete information on the items and on the water medium. Only after the maximal arrival of

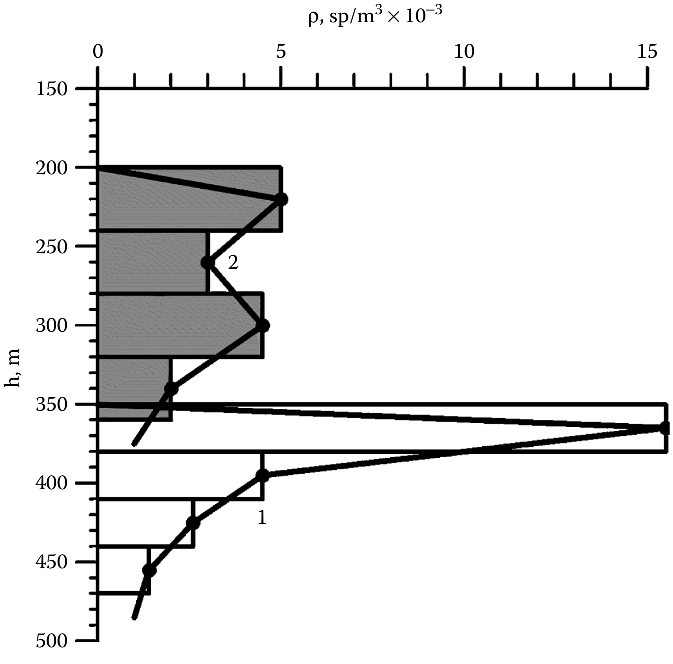

FIGURE 7.1 April 1981, North Atlantic. Distribution of the volume density of blue whiting concentrations by depth: 1, during the daytime; 2, during the nighttime (Ermolchev, V.A., personal communication).

fish is established is a detailed survey accomplished. If a survey is carried out in a region of fisheries, rapid fisheries-acoustic surveys are conducted instead of preliminary investigation. Their results easily allow for establishing the peculiarities of the distribution of commercial items (see Chapter 8).

CHOICE OF THE TIME FOR THE SURVEY INITIATION

It is known that fish nearly always move permanently; therefore, it is hard to encompass all the population in a survey. Only in rare cases does the population of some species of fish form nearly immovable local concentrations within periods of spawning or wintering. Estimation of such concentrations provides a complete enough notion of the stock of population. However, the stocks of many fish species are estimated along their routes of migration, when they concentrate at traditional places within the period of fattening, spawning, or wintering. Carrying out surveys of such areas allows researchers to obtain information comparable by years and seasons on the state of stocks.

A major condition of efficient stock estimation consists of the choice of the time for initiation of an acoustic survey. To ensure conformity of the biomass received from the data of the acoustic survey to the state of the stock, the investigation is conducted at the time of maximal approach of fish to the traditional area. If commercial items inhabit depths mainly near the bottom, periods of conducting acoustic surveys should be additionally coordinated with the minimal masking of bottom fish, when concentrations keep separately above the bottom and errors of acoustic instruments are comparatively small. When indicated, the time for the initiation of surveys is determined from the retrospective data.

Unfortunately, the precision of forecasting the time for initiation of a survey in a chosen region is usually not high. In addition, for organizational reasons, no survey is often done in the time fixed. As a result, upon completing a survey, it is often unclear just what part of a commercial stock was investigated; that is, the value of a biomass obtained in such a way is random. Therefore, in preparing a forecast, biologists, not confident of quantitative survey results, do not use the value of a biomass, but rather the tendency of this value to change as compared to previous years, which is, also, not always correct.

Experience shows that the correct time for initiation of a survey becomes available only after a preliminary investigation of a region; respectively, it is possible to receive a reliable value of a biomass characterizing the value of a stock. It becomes possible to do this most accurately when carrying out fisheries-acoustic surveys or prolonged passing observations (see Chapter 8 and Chapter 9).

THE CHOICE OF THE SURVEY TYPE

For estimating a biomass of commercial concentrations within the water column, an acoustic survey is usually sufficient. When fish are distributed near the surface or the bottom, it is necessary to carry out a combined, trawling-acoustic survey. Before the beginning of a survey, the extent of masking of a surface or a bottom concentration is elucidated, and the coefficient of masking of the readings of an acoustic instrument K_M is determined from formula (6.24). If the masking is insignificant ($K_M < 0.1$), an acoustic survey is conducted. With a value of K_M up to 10, a trawling-acoustic survey is undertaken and, with a value of K_M exceeding 10, a trawling one is carried out. Sometimes, to reveal the general distribution of surface concentrations, an aircraft survey is conducted or satellite information is used.

THE CHOICE OF THE SURVEY MODE

The forms of mode includes the grid of transects, the unit of sampling distance, the speed of vessel movement, and the time of day during which an acoustic survey is carried out.[5]

The grid of transects is determined by the direction of movement, the grid pattern, and the distance between transects. If the item distribution is unknown or has been only slightly studied, a preliminary survey is carried out for outlining the area of item habitation and tentatively estimating fish quantity. If the item distribution is known well enough, a detailed survey is conducted with the purpose of more precisely estimating the concentration density and biomass.

When choosing the grid of transects, it is necessary to pay the most attention to areas of the region under survey most favorable for the formation of commercial concentrations. Transects should intersect frontal, gradient and so-called ergocline zones; the latter refer to areas of contact, mutual penetration, and mixing of water masses accompanied by various physical phenomena (fluxes, eddies, upwelling, waves, etc.). When surveying a bottom concentration situated over a complicated, broken relief, it is necessary to locate transects within a small angle or along isobaths; otherwise, transects will be very short.

The direction of motion is also important in surveying moving concentrations. The path and speed of horizontal migrations can be determined with the help of sonar with a panoramic or sector view with electronic scanning, as well as with measuring devices using the Doppler effect. If the direction of movement of items under survey is discovered, it is necessary to locate transects so that they will be perpendicular to the path of the fish motion, while the general direction of a survey should be opposite to that of the migration. For this purpose, it is necessary to progress along a concentration and to reach heading schools; then a survey is carried out in the opposite direction. If the speed of fish movement is known, it is taken into account in treating the survey data (see Section 7.2).

The survey pattern represents either zigzag or parallel transects. Zigzag transects are the more economical survey pattern. The efficiency of both patterns was investigated by means of a mathematical simulation of concentrations and surveys (see Section 7.3). For increasing the efficiency of acoustic surveys of slowly moving concentrations, it is expedient to design a double grid of transects; for example, double zigzag with a shift (a so-called interleaved survey).[6–8] In this case, the item distribution and biomass are ascertained after the first pass; as a result of the second one, the survey data are defined more precisely. Survey interruption because of unexpected circumstances leads to smaller losses when using such tactics.

It is important to correctly choose the distance between transects in designing surveys. The choice of acoustic transects depends on the character of nonuniformity of the field of density of commercial concentrations. The transects intersecting a relatively uniform distribution of measured fields should be located at water areas rarer than those crossing places with abrupt variation of concentrations under survey. The distance between transects is usually designed to be constant if the character of a distribution is unknown, as well as for comparatively homogeneous commercial concentrations. Under a very nonuniform structure, the region of a survey is divided into sections with comparatively uniform distribution (strata); in this case, the distance between transects on each stratum is designed to be constant, while on various strata it can vary. Tentative values of the distance between transects are, regarding a large-scale survey, up to 50 miles and more; with respect to a small-scale survey, from 20–30 down to 4–5 miles or less, depending on the suggested area of work.

The valid choice of the distance between transects of an acoustic survey is a complicated problem; for its solution, it is necessary to calculate and to analyze the statistical characteristics of the fields of density of concentrations under survey. The values of a density at areas of concentration, located closely enough, one to another, can be correlated; i.e., statistically connected. It is clear that, in locating transects along these areas, the estimate of the biomass is less precise than that obtained as a result of studying the areas of a concentration with uncorrelated values of density. On the other hand, too great a distance between transects of an acoustic survey leads to a decrease in information on the density of concentrations within the areas located between transects.

One of the characteristics of a random field of density of concentrations is the autocorrelation function.[9,10] An optimal distance between transects is chosen on the basis of calculation of the radius of autocorrelation R; i.e., the maximal distance at which the values of the density are statistically connected. The autocorrelation radius is determined from a plot of the autocorrelation function as the distance from the coordinate center to the point where the lag (autocorrelation) is zero.[9] The function of autocorrelation of the field of density of concentrations of Antarctic krill is presented in Figure 7.2 as an example.[5] The distance between transects is chosen close to the distance at which the autocorrelation function comes to the abscissa axis. Questions of choosing the distance between transects on the basis of the autocorrelation radius are considered in greater detail in Section 7.3

Besides the autocorrelation function and radius, an important statistical parameter, widely used in acoustic biomass estimation, is the average value of the density. In the general case, the average density is determined as:

$$\bar{\rho} = \frac{1}{XY} \iint_S \rho\,(x,y)dxdy \tag{7.1}$$

where ρ is the density of concentrations studies, x and y are the coordinates of the point of measuring the density, X and Y are the length and width of the water area studied, and S is the area of the region under investigation.

With an isotropic distribution of the density field in the working area, the average values of the density are independent on one of the coordinates; i.e.,

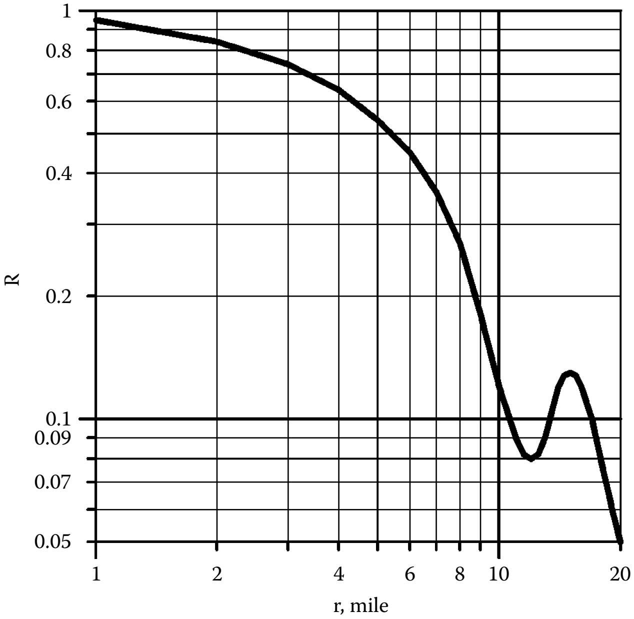

FIGURE 7.2 Autocorrelation function of concentration density of Antarctic krill from the data of the acoustic survey carried out in 1981.

$$\bar{\rho} = \frac{1}{X}\int_0^X \rho\,(x)dx \tag{7.2}$$

This means that, in the case of isotropy, the determination of the average density can be reduced to the treatment of data of measurements on linear areas; i.e., on transects.

The unit of sampling distance is the length of a survey transect along which acoustic measurements are integrated and averaged to receive one sample. If the sampling distance unit is too large, potentially useful information about the distribution of the stock will be lost. If it is too small, successive samples will be correlated, in which case it will be difficult to determine the confidence interval for the stock estimate.[6] The unit of sampling distance may be as short as 0.1 miles to distinguish dense schools, or as long as 10 miles in the case of species widely distributed over large expanses of the ocean; usually, the sampling distance unit may be within a range of 1–5 miles.[6]

As will be shown later (in Section 7.3), it is expedient to take the unit of sampling distance close to the autocorrelation radius of the field density in the direction perpendicular to a survey. In this case, density readings from an integrator will be independent, and the error of the biomass estimate will be minimal. The unit of sampling distance as short as one to two miles is taken for calculating statistical characteristics of density fields.

The speed of vessel movement is chosen so disturbances on the transducer of an acoustic instrument will be weaker than useful echo signals, as well as taking into account the value of excessive sound attenuation in the surface aerated layer of the ocean (see Section 2.1 and Section 6.4). The speed of movement depends on the type of vessel and is usually equal to 9–11 knots; it is reduced to 5–8 knots during rough weather.

If possible, a survey lasts 24 hours a day. Limitations in the time of day may be connected to the peculiarities of behavior of items under study. For instance, many pelagic fish rise to the upper water layers at night and are poorly registered by acoustic instruments; surveys of such items are carried out during the day. In contrast, bottom items are often studied at nighttime when fish keep separately above the bottom and are better registered by acoustic instruments.

THE CHOICE OF SURVEY DURATION

In planning the duration of multidisciplinary surveys, designers have to make a choice between fewer measurements, advantageous from the point of view of the value and duration of work, and a large number of measurements, which allow the investigation to be accomplished in detail. A compromise is usually made between the former, leading to a lower accuracy of the survey results, and the latter, when the asynchronous data, because of the long duration of measurements, depreciate the results of the survey and lead to an abrupt increase of the value of the work.

The survey duration depends on the number of vessels allotted for this purpose and on the limit of time for their use. The high cost of expedition work does not allow for carrying out multidisciplinary surveys of a long duration. As a rule, an acoustic survey can last 10–15 days with one or two vessels, depending on the importance of the study and the suggested area of work.

The number of vessels allotted for a survey is determined by dividing the actual duration of work by the limit of time, depending on the designed allowable duration of the survey. Our investigations show that it is expedient to determine the allowable duration of a survey taking into account the nonsimultaneity of measurements, which occurs as a result of the variability of fish concentrations and oceanographic processes in time and in space. As follows from relation (7.8) (see Section 7.3), the allowable duration of a survey can be tentatively calculated from the following formula:

$$t_{surv} = \varepsilon_a l_{surv} / v_{fish} \tag{7.3}$$

where ε_a is the error because of nonsimultaneity of measurements, l_{surv} is the diameter of the area of a fisheries region under investigation, and v_{fish} is the speed of movement of fish concentrations.

For example, if the extension of the region under investigation is equal to 350 miles and the averaged speed of the concentration movement is 0.3 knots, then the survey duration with $\varepsilon = 20\%$ (0.2) is equal to:

$$t_{surv} = \frac{0.2 \times 350}{0.3} = 233 \text{ hours} = 9.7 \text{ days}$$

The actual duration of an acoustic survey depends on the suggested general length of the path of the designed survey and the speed of vessel movement. If the length of transects is taken approximately equal to l = 2000 miles and the average speed of the vessel movement v_{surv} = 8.0 knots, the actual time for carrying out an acoustic survey is:

$$t_{fact} = l/v_{surv} = 2000/8 = 250 \text{ hours} = 10.4 \text{ days}$$

Taking into account the oceanographic and trawling stations, as well as probable deterioration of weather conditions, the actual time for conducting a multidisciplinary survey is generally increased twofold; i.e., t_{fact} = 20.8 days.

As a result, the number of vessels allotted for a multidisciplinary survey in our case should be

$$n = t_{fact}/t_{surv} = 20.8/9.7 = 2 \text{ vessels}$$

A detailed survey is planned based on all of the information available on items, the region, water medium, and the results of preliminary investigations. Taking into account the general tendency to shorten a survey, all passing investigations conducted simultaneously, except the controlled fishing, should be reduced to a minimum.

7.2 SURVEY DATA COLLECTION AND TREATMENT

As mentioned at the beginning of this chapter, the following characteristics are determined during acoustic surveys: the biological composition and the density and biomass of fish concentrations, as well as the oceanographic parameters of the environment. As a result of carrying out a great number of accounting surveys, information on areas and regions is accumulated, and a database is created. The treatment of this massive amount of data provides the possibility of dynamically studying the variation of the fish distribution and quantity in connection with the environmental parameters and the biological condition of items, in order to more reliably solve the problems of forecasting commercial resources.

DETERMINATION OF ICHTHYOLOGIC CHARACTERISTICS

The composition and the biological state of fish concentrations are determined from control catches and fixed in the ichthyologic register. The information on the structure of commercial concentrations and the fish behavior is obtained from echograms of acoustic instruments. Values of the density of fish concentrations and their distribution are found as a result of integration of echo signals during a survey. These data are fixed in the acoustic register; the notes on echograms and integrams are made.

The species, length, weight, age, and sexual composition of concentrations, as well as the maturity, fatness, character of feeding, stomach content, and other characteristics are determined from biological samples of catches. In carrying out surveys of mixed concentrations, a greater number of controlled catches is required than in estimating single species concentrations.

The length composition of fish concentrations can be determined, without their being caught, by readings of the special equipment. It is possible to continuously observe the histogram of the length composition of concentrations along the course of a vessel on a display screen of the equipment. A histogram allows for judging whether large or small fish prevail. A histogram gives information not only about the length composition but also on species composition. Abrupt changes of histograms are controlled by trawling catches to verify their correctness.

The density of concentrations is determined by standard methods. The corresponding treatment of integrated echo signals allows for receiving the area and volume densities of concentrations within layers at different depths. The area density is used in drawing plane tables and in calculating the biomass. The volume density gives an idea of the distribution of concentrations; this is necessary in studying the regularities of fish behavior, in estimating the commercial significance of concentrations, and for other purposes.

Information on the structure of commercial concentrations, their depth and thickness, are received from echograms of acoustic instruments. Graphs of the vertical distribution of the volume density of concentrations are plotted using the values of density obtained in different channels of integration. Such graphs are mapped regarding various sections of a region under survey and during different times of day.

The values of the area concentration density, obtained from acoustic data, are plotted on a plane table.* If mixed concentrations are studied, separate maps regarding each species are drawn.

Plotting of distribution of concentrations is made by one of two methods: isolines of the density or localized areas. According to the method of isolines, the entire range of the values of density is divided into several gradations; isolines are drawn, representing the borders of the concentration areas with the density attributed to each gradation. According to the method of localized areas, the entire region is divided into sections (strata) with comparatively uniform structure; in designing surveys in traditional regions, for the sake of convenience of the treatment and in order to produce the results by seasons and years, it is possible to use equivalent squares as strata.

The application of the instrumental method of estimating the length composition of concentrations provides the possibility of plotting plane tables of the distribution of the density by size (age) groups of fish. For this purpose, at places of noticeable change of the length composition, readings of the percentage relation of the length groups are taken; then the length composition is reduced to an age one. The values of the concentration density are determined; these values are plotted on the plane table and the isolines of the density distribution for each length or age group are drawn.

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* Currently, plotting of plane tables of fish concentrations is automated and done with the help of computers.

With abrupt variations of the spatial distribution of commercial concentration at areas of depth overfalls or a junction of currents and so on, gradients of the density are determined and their location on a plane table is fixed by special treatment of echo signals. The isolation of gradient zones with abrupt jumps in the density is important in studies of the impact of oceanographic characteristics of water masses on the distribution of concentrations.

After dividing the plane table of the region under survey by gradations or by strata, the number of readings of the density corresponding to each gradation or stratum is determined; the average density in each gradation or stratum is calculated. The average values of density in combination with isolines of the density or localized areas characterize the distribution of concentrations under study within the surveyed area.

The method of isolines gives one the possibility of obtaining a clear picture of the distribution with the revelation of centers of the density; if such clarity is important (for example, in studying interrelations of the item distribution under medium conditions), it is expedient to draw isolines of the density. The method of localized areas allows easier automating of the treatment of data; therefore, it is preferable when the major aim of a survey is biomass estimation, especially over a large area.

In carrying out surveys of migrating fish, the distribution of concentrations on a plane table is distorted. In order to reduce the distribution to the real one, a so-called back lying of transects is conducted taking into account the speed of the vessel and fish movement (see Section 7.3).

In treating survey data by the method of isolines of the density or localized areas, the order of calculating the biomass is the same. The value of biomass of concentrations is obtained as a product of the average area concentration density by the area of a surface occupied by them. The biomass is calculated regarding each gradation or stratum and summed up. In an analogous way, the biomass with respect to each age group of fish is calculated. In carrying out surveys of a mixed concentration, the biomass of each species is determined.

The estimate of biomass is accompanied by the confidence interval; i.e., the borders within the limits of which this estimate is confined with a certain degree of reliability. In order to determine the confidence interval, the variance of the values of measured density is found first; then, the errors of the biomass estimate in each gradation of the density and its summary value are found. After this, the confidence interval is calculated.[5,11] The value of the confidence interval, to a certain degree, characterizes the quality of a survey.

DETERMINATION OF OCEANOGRAPHIC CHARACTERISTICS

In determining meteorological, physical, chemical, and biological characteristics of water masses, all available sources of information are used: radio translations, maps of the weather conditions translated by meteorological services, data of measurement made by observers aboard fisheries vessels in the region under survey, and results of the remote location of surface layers of the ocean from planes and satellite apparatus. Horizontal schemes and vertical transects of the distribution of various characteristics are drawn.

Radio-transmitted meteorological data by various organizations of the weather service, weather maps, and the forecast information are regularly received and generalized. The mentioned operative data are augmented by results of one's own meteorological observations; all the information is fixed in the register.

Operative physical and chemical data are regularly received and generalized. If the station of reception of the satellite information is available aboard a vessel, maps of the distribution of surface temperature in the ordinary and the infrared ranges are obtained. Water temperature of the ocean surface is measured continuously. In carrying out oceanographic stations, the temperature and salinity are measured, as well as chemical water characteristics at various depths.

If an electronic measuring complex is available, these measurements are conducted as to the vessel motion. The wave height and the direction and speed of currents are also determined. All data are fixed in the register. Horizontal maps and vertical graphs of the mentioned characteristics are plotted for the surface and at the depths of located fish concentrations. Schemes of the water dynamics are plotted as well.

In carrying out oceanographic stations, plankton is collected with conic nets from the surface to depths of 100 m and, when necessary, from greater depths. If special towed equipment is available, measurements of biological characteristics in the surface layer are conducted from a moving vessel. The plankton is collected by planktonic trawl from a moving vessel as well.

In the course of trawling at various depths and with bottom trawls, plankton is collected with the plankton net; samples of the benthos are taken by a drag. All the mentioned data are stored in the register. Maps of horizontal and vertical distribution of the plankton within the layers of measurement are plotted, first of all, at the depths of located fish concentrations.

The depth and the character of the ground are continuously measured in the course of a survey; the color and the water transparency are determined, as well as the location of abrupt depth overfalls and underwater heights. Visual observations on concentrations of birds, marine mammals, and other phenomena at the water surface are carried out. The mentioned information is stored in the register.

7.3 ACOUSTIC SURVEY ERRORS

Errors in acoustic survey results can be caused by factors connected to the medium, fish behavior and reaction, the quality of the survey design, and other factors. The impact of the medium, to a great extent, is determined by weather conditions. Thus, the sea roughness strengthens noises and sound attenuation in the surface layer. In order to continue a survey during rough weather, it is necessary to reduce the speed of the vessel or to change the direction of transects. Heavy weather forces an interruption of the survey; for this reason, a part of a region can remain uninvestigated.

Fish behavior affects the reliability of survey results, as the item distribution depends on it. When distributed near the surface or the bottom, part of a concentration can be undetected by instruments; this fact leads to underestimation of the density and biomass. The reaction of fish avoiding a vessel results in a similar underestimation. Daily vertical migrations and the variation of fish behavior under the impact of environmental conditions (illumination, temperature, weather) change the aspect of insonification of fish. This circumstance, as well as peculiarities of the biological state of the fish (spawning, fattening) can influence the item reflectivity; in using data from stationary measurements, it causes errors in estimates of the density and biomass.

As mentioned in Section 7.1, in designing and carrying out acoustic surveys, it is important to take into account the degree of nonuniformity of the random field of the concentration density, as the required density of the grid of transects and the unit of sampling distance, as well as the method of data treatment, depend on this nonuniformity. In addition, the direction and speed of horizontal migrations should be taken into consideration in survey design to avoid distorting the item distribution and the appearance of a corresponding error in biomass estimation. An additional contribution to the error of survey results introduces mistakes because of the asynchronous character of measurements and an incorrect choice of the time of initiation of the survey.

The following types of errors in survey results are differentiated: the bias of the biomass estimate and the unbiased error of the distribution of items under study.

THE BIAS OF THE BIOMASS ESTIMATE

The bias of the biomass is important in fisheries studies aimed at estimating the overall abundance of commercial items. The bias of the biomass estimate is described by its relative error. The part of the error connected to the medium of habitation of items under study, as well as to the peculiarities of their behavior, cannot be practically estimated. The following analytical dependence for the determination of the relative error of biomass estimation, taking into account the specifics of determining the concentration density in carrying out acoustic surveys, has been successfully established[12]:

$$\varepsilon_o = t_\beta a_1 \nu \sqrt{RD/S}$$

$$a_1 = \sqrt{2a_2}\ ;\ a_2 = \frac{1}{R}\int_0^R F\,(r)dr;\ t_\beta = \sqrt{2}\ \Phi^{-1}(\beta_1) \qquad (7.4)$$

where D is the distance between transects, S is the area of the survey region, ν is the coefficient of variation of the density values, F(r) is the value of the autocorrelation function of the density field at knots of the regular grid, R is the radius of autocorrelation, and $\Phi^{-1}(\beta_1)$ is the back Laplace function by a given confidence probability.

The table of the values t_β depending on the confidence probability can be found in mathematical reference books (for example, Reference 13). The calculation from formula (7.4) shows that, regarding walleye pollack, $a_1 = 0.15$, D = R = 18 miles.

With the coefficient of variation $\nu = 3.0$, the area of the region $S = 10^4$ mile², the confidence probability is 0.95, $t_\beta = 1.96$, the relative error of the biomass estimation $\varepsilon_o = 16\%$.

The accuracy of the biomass estimation was also determined by the method of mathematical simulation with the use of a computer. In simulating the fields of density, the following empirical expression was found for determining the relative error of the biomass estimation[14]:

$$\varepsilon_o = \frac{D^2 \nu^2}{S} \tag{7.5}$$

Calculating from formula (7.5) for the same example of walleye pollack, we obtain the relative error of the biomass estimation $\varepsilon_o = 29\%$.

It can be seen from the above example that formulas (7.4) and (7.5) do not result in a good correspondence of the accuracy of the biomass estimation. For establishment of the limits of applicability of these formulas, their thorough verification on various mathematical models of fields of density is required.

The error of the acoustic method of estimating the density of fish concentrations ε_m is determined by the quality of the equipment used, the conditions, and the character of registration and, in the case of applying the results of the stationary measurements of the reflectivity of items under study, by the extent of its having been studied. It was mentioned in Section 7.1 that the error of determination of the exact time of survey initiation (the maximal fish arrival to the area under survey) may result in great errors ε_t (up to 100% and more) in the biomass estimates. By carrying out regular fisheries-acoustic surveys before a survey of resources (see Chapter 8), this error can be reduced (to 10–20%).

The error of asynchronous character of measurements ε_a appears as a result of the measured data dissociation in space and time because of the variability of oceanic physical and biological processes and the comparatively long duration of a survey of resources. As a result of the asynchronous character, points of measurements, plotted on the plane table, are shifted relative to their actual positions. This leads to the distortion of a field under study on the plane table and, therefore, to an error in biomass estimation.

The shift of the position of measuring points on the plane table because of the asynchronous character of observations can be determined from the following relation:

$$\Delta l = l v_{pr} / v_{vess} = t_{surv} v_{pr} \tag{7.6}$$

where l is the summary length of transects from the survey beginning to the current measuring point, v_{pr} is the speed of the process of variability of the measured parameter, v_{vess} is the speed of vessel movement along transects of the survey, and t_{surv} is the duration of a survey.

If the directions of v_{pr} and v_{vess} are the same, the plane table is stretched; if they are opposite, the plane table is compressed. Therefore, for the purpose of reducing the extension of a survey, and consequently the duration of work, the general survey direction should be opposite to the fish movement.

An example of a plane table of the distribution of commercial concentration is given in Figure 7.3; the distortions are connected to the fish movement. The plane table of the concentration is built up as a result of an acoustic survey with zigzag transects; the general survey direction was opposite to the fish movement. The overall length of transects is $l = 1250$ miles; the speed of the vessel is $v_{vess} = 8.0$ knots; the survey duration is $t_{surv} = 1250/8 = 156$ hours $= 6.5$ days; and the speed of fish motion is $v_{fish} = 0.4$ knots.

The real dimensions of the fish concentration are established on the plane table by the method of back lying of transects. For this purpose, with the help of the above-mentioned relation (7.6), the shift of the points of the turn of transects is determined. Plotting the points of the shift on the plane table and connecting them with the lines, the shifted transects are received.

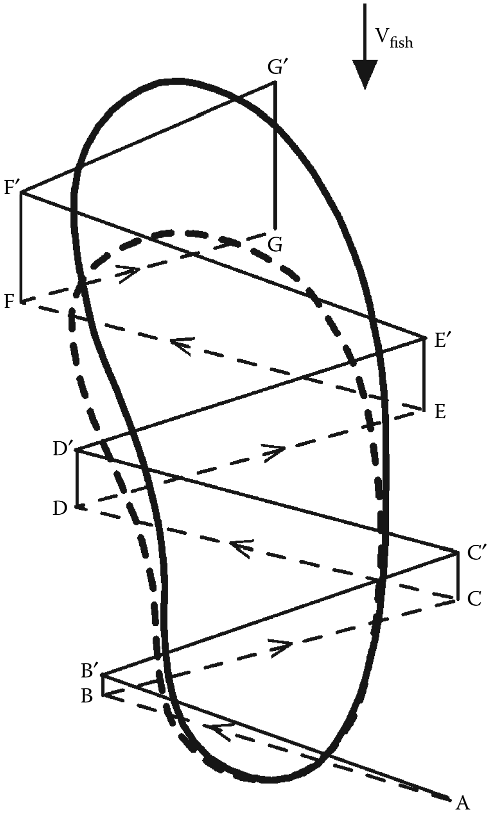

FIGURE 7.3 Scheme of the back lying of transects and determining the real contour of a commercial concentration (solid lines indicate the corrected transects and the real contour of the concentration; dashed lines show the actual transects and the measured contour of the concentration).

The calculation shows that the area of commercial concentration, obtained as a result of the survey, is 30% smaller than the actual one. This means that, because of the distortions on the plane table, the calculated value of the biomass will also be approximately 30% underestimated. It should, however, be noted that the value of the biomass may differ even more strongly from the actual one with a redistribution of the density field, which is possible during the survey.

Plane tables of the distribution of oceanographic characteristics because of the motion of water masses under the impact of currents are disturbed analogously. It is natural that the incompatibility of measured fields of fish concentrations and oceanographic elements owing to the lack of correspondence of their location and shape on a plane table to the actual space distribution, to a great extent, hampers the use of the results for studying relationships.

The error caused by the asynchronous character of observations can be estimated in a simplified way if the shift in the position of measuring points (Δl) is taken proportional to the extension of fields under study (l_s) on a plane table. Then the error can be determined from the following relation:

$$\varepsilon_a = \Delta l / l_s \tag{7.7}$$

Substituting formula (7.6) into this relation, we obtain the following expression for determining the error:

$$\varepsilon_a = t_{surv} v_{fish} / l_s \tag{7.8}$$

It follows from expression (7.8) that a knowledge of the general direction and the average speed of fish movement makes it possible to partially compensate for the error ε_a, introducing into an estimate the corresponding correction. Average values of the speed and direction of fish movement are determined from recordings of sonar and an echo sounder on a vessel at rest, as well as from the results of measurements made with the help of split-beam acoustic equipment. Mechanical or Doppler measurers determine currents.

Using formula (7.8), let us determine the error ε_a regarding the estimation of commercial resources of walleye pollack of the Far East in the region under survey. The extension of the region l_s = 500 miles, the speed of the concentration motion v_{fish} = 0.3 knots. The duration of the survey of the water area t_{surv} = 7.0 days (168 hours). Then

$$\varepsilon_a = \frac{168 \times 0.3}{500} = 0.10$$

As various components of the error can be considered independent, the formula for the resulting error of the biomass estimate can be expressed as follows:

$$\varepsilon_{bias} = \sqrt{\varepsilon_o^2 + \varepsilon_m^2 + \varepsilon_t^2 + \varepsilon_a^2} \tag{7.9}$$

In the considered case of walleye pollack of the Far East, $\varepsilon_o = 0.16$ and $\varepsilon_a = 0.10$. We will take the error of the acoustic method of the biomass estimation to be equal to 0.20. Let us also consider that, because of inaccurate determination of the time of mass fish arrival to the region, the error of the survey initiation $\varepsilon_t = 0.10$. Then

$$\varepsilon_{\text{bias}} = \sqrt{0.16^2 + 0.20^2 + 0.10^2 + 0.10^2} = 0.29$$

Survey experience shows that, in conducting regular investigations of the same commercial regions, using identical methods and means, the error of biomass estimates considerably decreases. Regarding surveys carried out for the needs of fisheries, the results received allow for choosing the distance between transects based on the given value of a bias of the biomass estimates.

It was mentioned in Section 7.1 that, if the item distribution is unknown or has been only slightly studied, a preliminary survey is carried out first; then, on the basis of the data received, a detailed survey is conducted. Determination of statistical characteristics of fields of the concentration density will allow, based on formulas (7.4)–(7.9), for operatively correcting the distance between transects during the course of an acoustic survey and, thus, refusing completely the study of a region by two steps. Preliminary works have shown that such a tactic is quite possible.[15]

UNBIASED ERROR OF THE ITEM DISTRIBUTION

Since acoustic surveys began to be used for ecological purposes (see, for example, References 16–20), it is often necessary to estimate interrelationships in the organization of populations. Therefore, an analysis was carried out of the efficiency of various survey patterns without considering the bias (References 7, 8, 21–25).*

The parameters of a reconstructed field and of that originally generated were compared by the method of mathematical simulation. Fish and zooplankton distributions in Lake Kinneret (Israel) were used as prototypes in simulating patchy fields. An unbiased reconstruction of the field was considered; the coefficient of determination between the reconstructed field and its original was used as a measure of the survey quality.

The mathematical model is based on the approach described in Kizner et al.[26] and Zaripov et al.[27] The surveyed area is a rectangular array of numbers making up a square matrix. Each number represents the value of a field in an elementary area (node). To simulate a distribution field, patches are generated and placed into the surveyed area. Outside patches, the field variable is zero or a constant background. Inside a patch the variable increases from the outer border towards the center according to a law obtained by analyzing data from real acoustic micro surveys.[28]

Patches may be circular (nondirectional) or elliptical (directional), with various sizes and spatial orientation, and separate or overlapping (partially or fully), forming larger patches with more complicated shapes. Patches are either immovable (static) or movable (dynamic); moving patches have a realistic shape like a comet.[29] Random fluctuations in density can be superimposed on the simulated patchy field. As a characteristic of a field, its autocorrelation radius in various directions is used; R and R_p are the autocorrelation radii in the direction of a survey and in the perpendicular direction, respectively.

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A resulting (constructed) patchy distribution field is then sampled by simulating an acoustic survey. We distinguish the general direction of a survey and the survey path. The survey direction coincides either with the abscissa or ordinate axis. The survey path, with an overall length l, is formed by transects disposed as parallel lines or a zigzag.

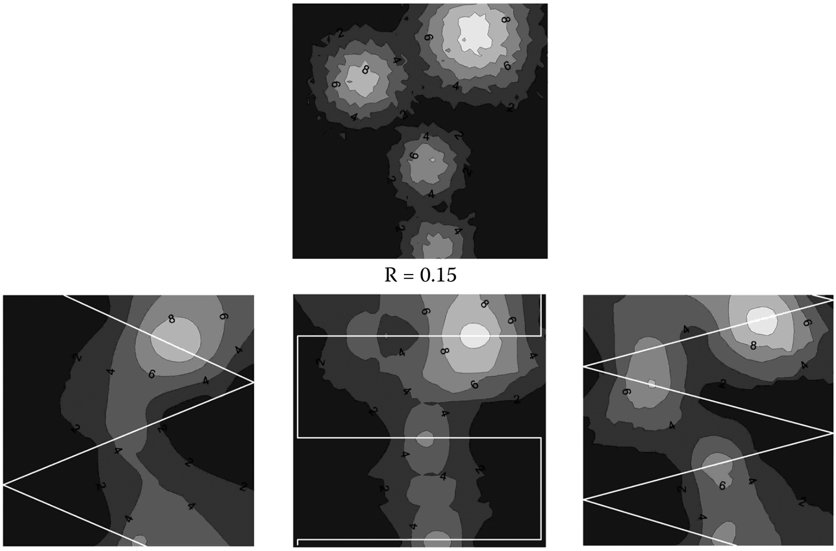
Transects as parallel lines are disposed perpendicularly to the general survey direction. Thus, the overall survey path in this case consists of parallel transects and connecting tracks perpendicular to transects. The distances between parallel transects are regular and equal to the length of connecting tracks (D). A zigzag is characterized by the shift between neighboring parallel transects in the general survey direction. The shift is a move of a survey when passing from one transect to another. The shift between neighboring parallel transects is regular and twice as large as the distance between corresponding parallel transects. Half a shift between neighboring parallel transects will later be designated as a distance between zigzag transects (D).

Along transects, a unit of sampling distance can be set. This distance is the length of a transect over which the values of a field are integrated and averaged to receive one sample. In the model, the sampling distance unit (d) is equal to a specific part of the transect length. Later, l, D, and R are given in proportion to the size of the square representing a surveyed area, and d in proportion to the transect size.

The values of a field along the survey path over each sampling distance are considered to be measured without error and are used to reconstruct a field. The reconstructed field again consists of the full set of nodes of the array representing the surveyed area. The corresponding values of the reconstructed field and of that originally generated are then compared for all nodes. Their adequacy is evaluated by the coefficient of determination representing the square of the standard Pearson correlation coefficient (r).[30]

If the efficiencies of both survey patterns are compared under the assumption of fixed transect spacing, it means that the numbers of parallel or zigzag transects are equal to each other. However, as the length of a zigzag transect is always smaller than that of a parallel transect plus connecting track, the sampling efforts (the overall survey path or, in other words, the time for conducting a survey) for both patterns are not the same. Therefore, the efficiencies are often compared under the assumption of a fixed sampling effort, when the overall survey paths for both patterns are equal to each other. In this case, a greater number of zigzag transects compared to parallel ones may be carried out. As a result, the adequacy of reconstructing a field from data of a zigzag survey is expected to increase; determination of the extent of this increase is one of the objectives of our study.

The efficiencies of the surveys by parallel and zigzag patterns under both assumptions are considered on Figure 7.4 and Figure 7.5. An original circular static distribution field is shown in Figure 7.4, top panel. The autocorrelation radius for the field is equal to R = 0.15. The distribution fields, reconstructed under the assumption of fixed transect spacing, are shown in the bottom panel (left and middle



R = 0.15

D = 0.40; $r^2 = 0.52$ D = 0.40, I = 4.0; $r^2 = 0.66$ I = 4.0; $r^2 = 0.72$

FIGURE 7.4 An example of an immovable circular field. Top: original field; Bottom: paths of the simulated surveys and the reconstructed fields. Initially published in Kalikhman, I.L., Patchy distribution fields: Acoustic survey design and reconstruction adequacy, in *Environmental Monitoring*, Wiersma, G.B., Ed., CRC Press, Boca Raton, 465, 2004. With permission.

positions). To receive an objective comparison of the results of the surveys by zigzag and parallel patterns, not only the transect spacing is taken to be equal (D = 0.4), but also their locations (each parallel transect crosses the point where the middle of a corresponding zigzag transect is situated). A comparison shows that the zigzag pattern leads to poorer results than the parallel pattern does ($r^2 = 0.52$ and $r^2 = 0.66$). Later, the parallel and zigzag patterns (middle and right position) are taken under the assumption that a fixed sampling effort is allocated to both surveys (the overall survey paths for both patterns l = 4.0). A comparison of the results shows that, in this case, the survey by parallel transects allows one to reconstruct the original field with lower adequacy than does the survey by zigzag transects: $r^2 = 0.66$ and $r^2 = 0.72$. Now, let us consider the reconstruction of the dynamic distribution field with the following conditions (Figure 7.5): all of the patches move from right to left, uniformly and rectilinearly; simulated surveys by parallel or zigzag transects are undertaken in the direction opposite relative to that of the patch movement; the speed of the patch movement is 0.7 of that of the survey; the unit of sampling distance d = 1/7. In the left and middle columns, both surveys are shown simultaneously; to simplify the figure, the unit of sampling distance is not shown. The reconstructed field is compared with the average original one, which is given in the right column, first row. A situation that may be described by the Doppler effect occurs when the survey and the patches move in opposite directions (right column, second through fourth rows); the Doppler effect is also observed when the survey and the patches move in the same direction. As seen in the figure, the results, with regard to dynamic distribution fields, are exactly the same as they are with respect to static fields. The assumption of fixed transect spacing leads us to the following results: $r^2 = 0.55$ (zigzag pattern), $r^2 = 0.64$ (parallel one); the assumption of fixed sampling effort, $r^2 = 0.64$ (parallel pattern), $r^2 = 0.66$ (zigzag one).

As a result of a great number of numerical experiments, we arrive at the following conclusions.[25] In application to circular patches, the direction of an acoustic survey is not important; in the case of elliptical ones, the optimal survey direction coincides with the direction of the patch elongation. A patchy field can be reconstructed properly ($r^2 > 0.7$) if $D/R < 1.5–2.0$ (regarding a parallel pattern) or $D/R < 1.0–1.5$ (in respect to a zigzag one) and $d/R_p < 1.0–1.5$. To some extent, it is possible to compensate the change in the adequacy of the reconstruction of a patchy distribution field by an increase in the distance between transects and a corresponding decrease in the sampling distance unit, and vice versa. Practically, it is expedient to carry out a survey with a larger distance between transects and smaller unit of sampling distance.

If the transect spacing is fixed, the parallel pattern allows (with great probability) for more adequate reconstruction of an original distribution field (in cases of both immovable and movable fields) than the zigzag pattern does. In contrast, if a fixed sampling effort is allocated to a survey, the parallel pattern allows (with great probability) for less adequate reconstruction of an original distribution field (in cases of both immovable and movable fields) than the zigzag pattern does.

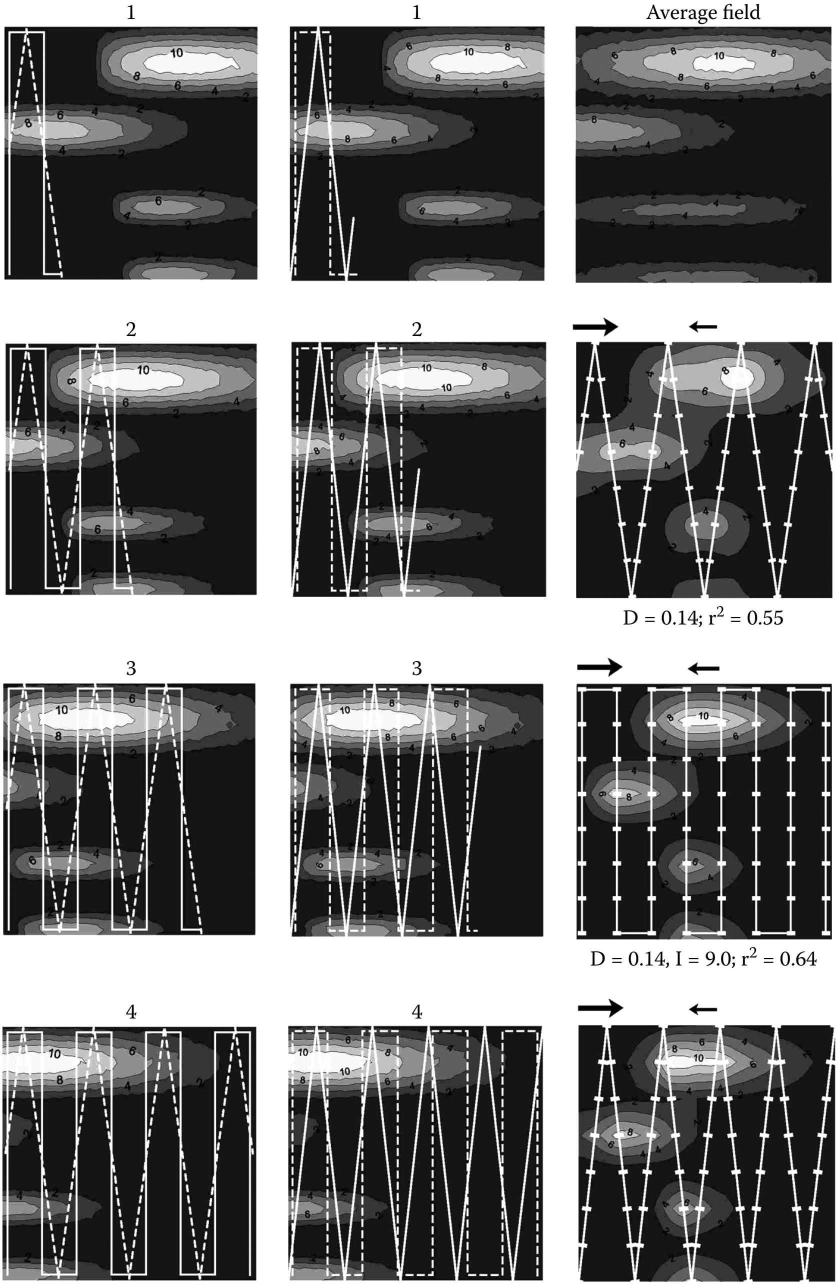
Regarding surveys, carried out for ecological needs (see Section 8.4), the results received allow for choosing the distance between transects and the unit of sampling distance on the basis of the given value of an autocorrelation radius for fields of density of commercial concentrations.

7.4 ACOUSTIC SURVEY PRACTICE AND PERSPECTIVES

Until recently, the estimation and control of biological resources in commercial regions was accomplished only with regard to the main species of fish. With the impact of fisheries on the multispecies community, the control of the one species does not allow revealing the mechanism of interspecies relationships and does not provide a complete picture about the real state and perspectives of exploitation of the entire stock. To ensure more precise regulation of fisheries, the control of the state of resources is required, not only with respect to the main species, but also with regard to the other species of the ecosystem.

A fisheries ecological system (ecosystem) is the entirety of biological items, functioning together and interacting with the abiotic environmental medium. A fisheries ecosystem, including a large quantity of various species of animals and plants, together with the processes occurring within it, represents, as it were, a single complex organism.

Under normal conditions, an ecosystem is in a stable equilibrium with strongly pronounced interrelationships between species. Abrupt changes of natural conditions may force the system out of its equilibrium. In this case, usual interrelationships between species break down; some species receive an advantage in the use of food sources of the system and begin developing faster than others. With time, when



D = 0.14; r^2 = 0.55

D = 0.14, I = 9.0; r^2 = 0.64

I = 9.0; r^2 = 0.66

FIGURE 7.5 An example of a movable elliptic field. Left and middle columns: the sequence of positions of the field and the surveys at the same moments of time (left column: the transect spacing is fixed; middle column: the fixed sampling effort is allocated to the survey). Right column, first row: the average original field. The fields are reconstructed from the results of the surveys under the assumption of fixed transect spacing (second and third rows) or fixed sampling effort allocated to the survey (third and fourth rows). Small arrows indicate the direction of the patch movement, large arrows indicate the directions of the surveys. Initially published in Kalikhman, I.L., Patchy distribution fields: Acoustic survey design and reconstruction adequacy, in *Environmental Monitoring*, Wiersma, G.B., Ed., CRC Press, Boca Raton, 465, 2004. With permission.

natural conditions become normal, such an imbalance is recovered from by the ecosystem itself.

Another case is when one or several species of the ecosystem are strongly affected by fisheries. Then, species not subjected to the fisheries receive favorable conditions for a rapid growth, as they are ensured free access to a food source of the ecosystem. In those cases, the press of fisheries, in combination with anomalous natural conditions, may abruptly break the stability of the ecosystem and lead to irreversible consequences, to a substitution of one species by another and, in the end, to a degradation of the whole system.* The ecosystem may jump to a lower level of structure and organization, when the species exploited by fisheries can no longer exist.

The exploitation by fisheries of stocks of the north basin is an example of a rough violation of ecological equilibrium. It leads to a misbalance of the ecosystems of the Norwegian and Barents Seas. The point is that the imperfect forecast of the fisheries withdrawal of the main fish species over many years promoted their intensive fishing. In the end, this resulted in the abrupt fall of the stocks of fish, shrimps, marine mammals, and colonial birds of these regions.

As another example, intensive fisheries of Atlantic-Scandinavian herring can be cited. In its time, the fisheries reduced the stock of this fish to such an extent that the authorities had to introduce a prohibition on its fishing for many years. Intensive fisheries of the Barents Sea cod also impacted fatally on its stock. As a result of decreasing the stock of cod, an abrupt burst in the quantity of capelin occurred. This was a reaction of the ecosystem to the reduction of pressure of the main predator, the cod. And again, irrational fisheries practically destroyed the large stocks of capelin within several years.

As shown by biological investigations, the major role in the abrupt decrease of the stocks of capelin and herring was played by the cod as predator, which consumed these fish in large quantities. This factor was not taken account when forecasting the commercial withdrawal of capelin and herring. The decrease of population proliferation, pollutions of the water medium, and other factors were never taken into consideration when forecasting. An analogous situation, connected to a breakdown in the equilibrium of a commercial ecosystem, took place in the Far East basin in connection with an abrupt decrease in the stock of pollack. The conditions of life for many species of marine items, to a great degree, depend on the quantity of pollack.

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* At this time, the pollution of the habitation medium of biological items begins to affect the stability and reliability of the functioning of ecosystems in many regions.

In order not to allow repetition of the mentioned phenomena, at present, acoustic surveys of biological resources are carried out regularly in nearly all of the main commercial regions of the World Ocean, including internal waters. Works aimed at the estimation of the zooplankton biomass by the acoustic method are conducted (References 31 and 32).*

In connection to establishing 200-mile oceanic fisheries zones, surveys of a commercial region carried out by the joint efforts of various countries find ever-growing application. Biological resources in fisheries regions cannot be divided because of the migration of items from one zone to another; therefore, the protection of stocks is a task common to all interested countries. International surveys of blue whiting and capelin in the North Atlantic, sprat in the Baltic Sea, fish of the "0-group" in the Barents Sea, and so on, are regularly carried out.** The results of estimating the distribution, abundance, and biomass, based on such surveys, and taking into account age and maturity as well as biostatistical indices, provide the possibility to judge the yield of separate generations and the spawning stock, to forecast the state of biological resources and to specify an allowable catch.

These surveys began in the north basin. For example, the distribution of the area density of 2-, 3-, and 4-year-old capelin in the Barents Sea is shown in Figure 7.6. The map was drawn on the basis of a survey carried out in the fall of 1984.[33] The survey showed that the main part of the stock (about 90%) constituted two- and three-year-old fish; the juvenile group (young fish) was sparse. Several large-scale trawling-acoustic surveys of the main commercial species of fish of the Barents Sea (cod, haddock, perch, and so on) were carried out within the period of their fattening. Soviet and Norwegian research vessels participated in the surveys. However, the results of the rather lengthy investigations did not prove to be entirely correct, in spite of the great expense: it was impossible to accurately estimate the quantity and biomass of commercial species because of the acoustical masking of fish readings near the bottom.

The surveys of Antarctic krill, within the framework of the international programs, were of an especially large scale. The enormous regions of Antarctic Ocean, encompassed by the acoustic survey by the "Fibex" program (1980–1981), are shown in Figure 7.7. Vessels of Argentina, Australia, Chile, France, West Germany, Japan, Poland, South Africa, the United States, and the USSR participated in this survey. The scientific vessel *Odissey* took part from the USSR; one of the authors was the survey leader. As a result of the survey, a possibility of detecting dispersed krill by acoustic instruments was found;[34] the krill distribution was established and their biomass was estimated.

In comparatively small lakes, where populations may have more distinctive shapes and can be studied synoptically, conditions for the analysis of

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* Estimation of zooplankton is carried out with the help of towed or extended transducers, operating at frequencies within a range of 0.1 to 10 mHz. Equipment with a very high resolution is used to measure the target strength of plankton.

** Fish no older than one year are understood to make up the "0-group."

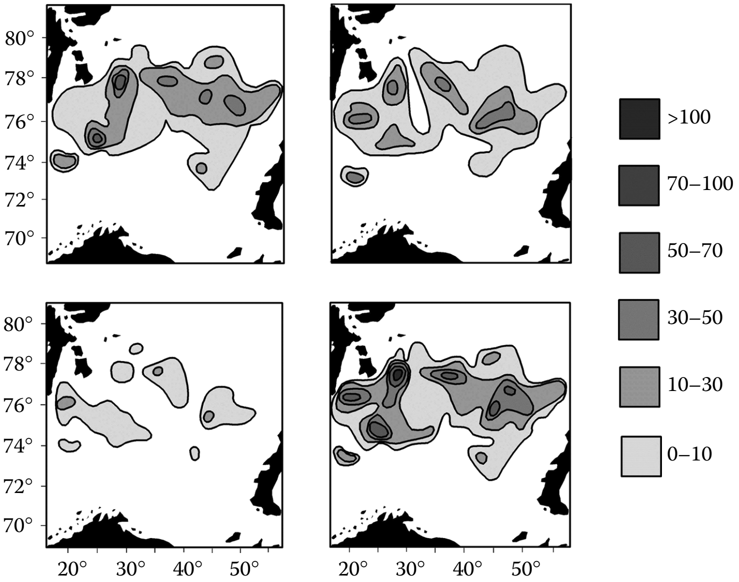

FIGURE 7.6 Distribution of area density of various ages of capelin in the Barents Sea from the results of the survey carried out in the fall of 1984. Top left: 2-year-old fish; Top right: 3-year-old fish; Bottom left: 4-year-old fish; Bottom right: overall density of all the mentioned groups. In the legend, the area density of capelin is indicated in tons/mile^2.

cause-and-effect links are more favorable than those in the open sea. In Lake Kinneret (Israel), a multidisciplinary survey program was established for this purpose, combining acoustic surveys of fish concentrations and concurrent limnological sampling at stations. Areas of contact, mutual penetration, and mixing of water masses with substantially different patterns, accompanied by various physical phenomena, are characterized by frontal zones where gradients are high. The survey, carried out on 25 December 1990, provided us with a possibility of observing such frontal zones in the eastern and the southern parts of the lake (Figure 7.8). They are likely to be areas rich in plankton and fish and, in reality, zooplankton and fish concentrated in these regions (Reference 4).* However, zooplankton density was low in the area where the fish density was maximal. Apparently, the process of fish predation dominated the factors causing aggregation of zooplankton in frontal zones. This example demonstrates the great potential of acoustic surveys in internal waters regarding the evaluation of the factors underlying the organization of the natural world. The results obtained were used for elaborating a method of identification of correlation zones for aquatic ecosystem component distributions.[35–37]

An objective estimation of the state of biological resources in a region under investigation, according to our opinion, is possible when surveys regarding various species are carried out during the most favorable periods. Within the period chosen

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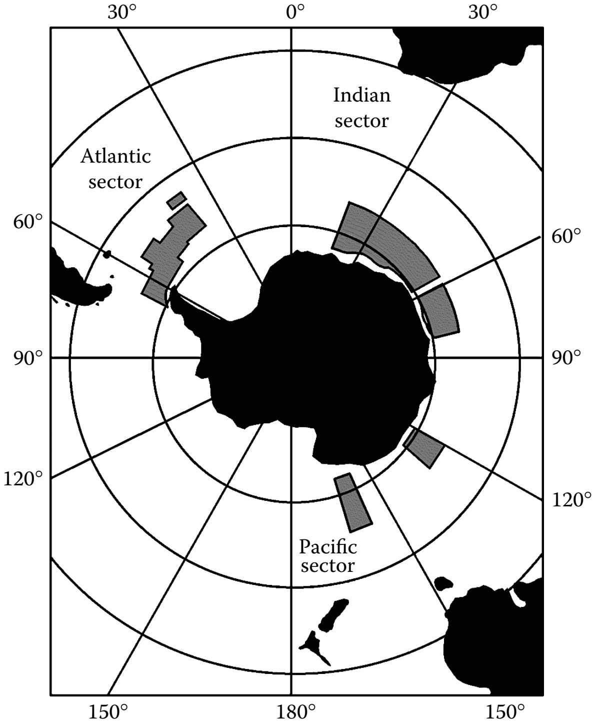

FIGURE 7.7 Scheme of location of regions of the acoustic surveys carried out within the framework of the program "Fibex."

for a survey, species under study should have a comparatively stable distribution and behavior; the main part of concentrations in the course of the survey should keep to a limited water area, separated from the bottom. To estimate fish food interrelations within the period of fattening, it is expedient to determine the degree of one species being eaten by another.

For conserving resources of the main commercial species of the regional ecosystem at a satisfactory level, not only their estimation and control are required but also the correct regulation of commercial withdrawal taking into account the inter-species and between-species fish interaction, competition, predation, cannibalism, and other factors. It is known that fish-predators often eat fish-prey in significantly greater quantities than those withdrawn by fisheries. Therefore, the correct regulation of a commercial withdrawal of main fish species is very important for the rational exploitation of the resources of a region.

Using preliminary studies, biologists try to balance the values of allowable withdrawal of the main fish species. Unfortunately, the criterion for withdrawal, ensuring a stable ecological equilibrium of commercial resources, has not yet been elaborated because of the complicity of accounting for the summary impact of various factors. With the poor level of study of the impact of natural conditions, food sources, and feeding interrelations on fish stocks, orienting fisheries towards a

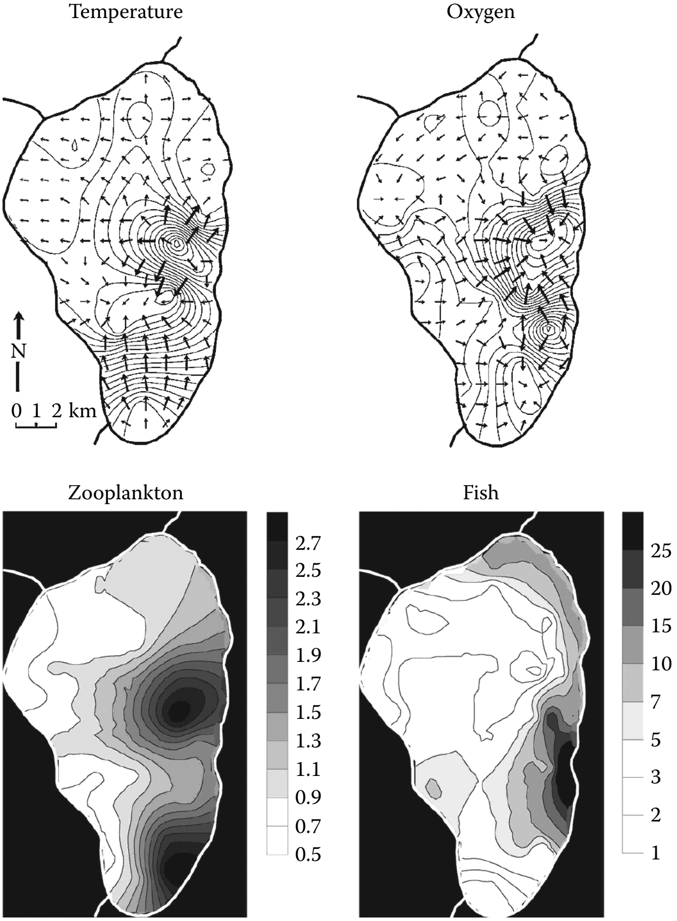

FIGURE 7.8 Lake Kinneret (Israel), 25 December 1990. Distribution of the following parameters: Top left: water temperature at the surface (from 18.8 to 19.1°C); Top right: dissolved oxygen concentration at the surface (from 6.8 to 8.4 mg l^{-1}) (vectors indicate the absolute value and direction of the horizontal gradient of water temperature and dissolved oxygen concentration); Bottom left: zooplankton density ($\mu g/l^{-1}$) at a representative depth of 2.0 m; Bottom right: area fish density (thousands specimens/ha). Kalikhman, I., Walline, P., and Gophen, M., Simultaneous patterns of temperature, oxygen, zooplankton and fish distribution in Lake Kinneret, Israel, *Freshwater Biology*, 28, 337, 1992. With permission.

maximal allowable withdrawal is still risky, taking into consideration the strained state of commercial resources. Underestimation of the negative impact of even one of the main factors can result in an unpredictable breach in the equilibrium of the commercial ecosystem of a region.

A rational ecosystem regulation of commercial withdrawal of biological resources, ensuring the optimal relation of main fish species of a region, will become possible only after in-depth study of the impact of oceanographic factors on the distribution, quantity, and biomass. Because of the great spatial and temporal variability of natural conditions and their impact on commercial resources, the detailed study of interrelations must be accomplished dynamically. In this sense, carrying out regular fisheries-acoustic surveys and accompanying oceanographic and trawling stations looks very promising (see Chapter 8).

At present, the preservation of biological resources and rehabilitation of seriously undermined by fisheries populations in the main oceanic regions is a more important task than the search for new commercial regions and items. If we take into account that the detection of new commercial regions becomes less probable from year to year, and expenses for their search increase, it must be clear that search works will gradually be extinguished.

In the near future, when all commercial regions will have been discovered and completely mastered, the estimation, control, and regulation of biological resources will assume an even greater importance. For this reason, the information and computing equipment discussed herein are now for use not only on scientific but also on commercial vessels. It is possible to predict that, in the not- too- distant future, a sustainable commercial fisheries will be unthinkable without using the integrating and other, more sophisticated, information and computing techniques for estimation of the biomass of commercial populations.

Wide use of equipment for determining the density and commercial significance on fishing vessels will allow for solving the problem of the estimation and control of biological resources of the World Ocean in a new way. Receiving data on the density of concentrations at locations of a commercial fleet, and translating these data from fisheries vessels to a waterside computing center, will make it possible to obtain a synchronous picture of the distribution and biomass of concentrations within a commercial region without carrying out expensive acoustical surveys; the permanent control and estimation of biological resources will become possible on a global scale.

7.5 ECONOMIC EFFICIENCY OF SURVEYS

Questions of estimating the economic efficiency of acoustic surveys are considered in the study by Kalikhman et al.[38] In estimating the economical efficiency (EF) of an acoustic survey, it is necessary to determine the difference between two factors: the economic return (ER) from the use of information gained as a result of the survey being conducted versus the expenses (EE) required to conduct the survey; i.e.,

$$\mathrm{EF} = \mathrm{ER} - \mathrm{EE} \tag{7.10}$$

The calculation of the economic return usually offers the main difficulty in estimating survey efficiency. Depending on survey aims, the approach to determination of the value ER can vary. One of the fixing requirements in designing a local search (see Section 3.2) or surveys of fishing conditions (see Section 8.2) is the allowable probability of detection of commercial concentrations, while, for acoustic surveys of resources (see Section 7.3), this becomes the error in the estimate of a concentration.

A Local Search

In this case, the economic return is characterized by the efficiency of operations of the commercial vessel on detected concentrations. This means that the value ER is the profit from fisheries of concentrations, which can be elucidated during the course of the search; i.e.,

$$ER = P_1(pY_f - Y_o) \tag{7.11}$$

where P_1 is the profit per one ton of marine production, \$/ton; p is the probability of detecting concentrations with the forecasted commercial significance; Y_f is the forecasted catch of recently detected concentrations, ton; and Y_o is the catch before detecting new concentrations, ton.

When designing a search operation, the probability of detection (p) of commercial concentrations is usually taken to be no less than 0.9 (see Section 3.2). The assumed catch Y_f is determined by *a priori* data of dimensions and of the commercial significance of concentrations. The values P_1 and Y_o can be estimated on the basis of the results of fisheries.

Expenses for carrying out a local search are connected with the cost of exploitation of a vessel under use. When working in a certain region with a given surveyed area, the value of expenses is proportional to the overall length of transects and passages, the cost of vessels used, and their allowable cruising speed.

The expression for calculating forecasted expenses for carrying out a local search regarding a parallel survey pattern has the following form:

$$EE = \frac{C_1}{v_{vess}} (1 + k)\,(l + L) \tag{7.12}$$

where C_1 is the cost of exploitation of a vessel per one day, v_{vess} is the cruising speed of a vessel, k is the coefficient accounting for time expenses of a force majeure, l is the overall length of transects, and L is the summary length of passages.

The cost of vessel exploitation C_1 depends upon its type. The allowable speed v_{vess} depends upon the weather. Under bad weather conditions, a survey is broken off. Time expenses for a force majeure constitute a certain part of the duration of the search works, dependent upon the weather. The value of the overall length of transects l is closely connected with the configuration and dimensions of forecasted concentrations. The extension of passages L depends on the remoteness of a survey from the base of vessels.

Substituting (7.11) and (7.12) into (7.10), we obtain the following relation:

$$EF = P_1(pY_f - Y_o) - \frac{C_1}{v_{vess}} (1 + k)\,(l + L) \tag{7.13}$$

Using relation (7.13), it is possible to tentatively determine the expected economic efficiency of the designed search operations.

Comparatively precise calculations of the economic efficiency are only possible when designing search operations within a traditional region, if the probability of detecting commercial concentrations is high enough and if the area of a region under study, dimensions of concentrations, their commercial significance, the species and length composition, and the profit per ton of marine production are known *a priori*. A rougher estimation of the economi efficiency can be made in designing search operations during anomalous years, when the fish distribution is known only in general terms.

SURVEYS OF FISHING CONDITIONS

The principles considered for calculating the economic efficiency can be analogously spread to surveys of fishing conditions. The economical return ER, regarding surveys of fishing conditions, is determined by the use, by commercial fleet, of short duration forecasts and recommendations of a research vessel, carrying out fisheries-acoustic investigations. The value ER is calculated as the difference between the catch by commercial vessels on forecast concentrations and the catch in the case when a forecast is absent; i.e.,

$$ER = P_1(Y_f - Y_o) \tag{7.14}$$

where Y_f and Y_o is the catch on forecast concentrations and with an absence of a forecast, respectively.

Expenses on carrying out surveys of fishing conditions depend on the cost of exploiting a research vessel; they are calculated as

$$EE = C_1(t_s + t_L + t_k) \tag{7.15}$$

where C_1 is the average cost of exploiting a research vessel per day, t_s is the duration of surveys, oceanographic stations, control fishing and other works during the expedition, t_L is the duration of passages, and t_k is the expenses of the time for a force majeure.

Substituting (7.14) and (7.15) into (7.10), we obtain the following relation:

$$EF = P_1(Y_f - Y_o) - C_1(t_s + t_L + t_k) \tag{7.16}$$

Using relation (7.16), it is possible to tentatively estimate the economic efficiency of surveys of fishing conditions.

SURVEYS OF RESOURCES

The economic efficiency derived from the increased accuracy of the estimation of biological resources by the acoustic method must become even more significant. The low accuracy leads to an erroneous determination of the commercial withdrawal.

This error may produce an estimate either higher or lower than the real value of an allowable catch, which may result, after all, in an under-catch or over-catch with all of the subsequent consequences. It only becomes possible to determine the degree of the influence of an under- or over-catch on the value of the stock in the following years based on expert estimates.

It is known that a stock overestimation leads to greater losses than an equal underestimation; therefore, the following consideration is made regarding an overestimation. Many years of exploitation of the same fish populations are typical for modern fisheries; therefore, it is suggested to estimate expenses and, hence, the ultimate economic efficiency taking into account the remote consequences of designing upon a number of future years. Let us consider that the commercial stock and the quantity of a spawning shoal decrease as a result of an over-catch during the period approximately equal to the average duration of the fish life. Let us also assume that the degree of decreasing a summary catch in years to come is proportional to the extent of an over-catch in the present year.

Based on these assumptions, we obtain the following expression for calculating the yearly expenses with an overestimation of the stock[38]:

$$EL = WKP_1\left[t - t_1\left(1+\varepsilon\right) - \frac{t - t_1}{1+\varepsilon}\right] \tag{7.17}$$

where W is the stock, K is the coefficient of commercial withdrawal, P_1 is the profit per ton of marine production, t is the average duration of the fish life, t_1 is the time equal to one year, and ε is the error as a part of one.

The use of acoustic information instead of biocommercial data allows for increasing the accuracy of determining the total allowable catch and decreasing expenses only if the acoustic information is more accurate than the biocommercial one. Such a situation can take place, in particular, regarding pelagic fish with a profoundly studied distribution and behavior, as well as fish with a short life cycle. The formula for calculating a yearly economic return has the following look:

$$ER = WKP_1\left[\frac{t - t_1}{1+\varepsilon_{bias}} - \frac{t - t_1}{1+\varepsilon_b} + t_1\left(\varepsilon_b - \varepsilon_{bias}\right)\right] \tag{7.18}$$

where ε_{bias} and ε_b are the errors of the acoustic and biocommercial estimates of the stock, respectively.

The reliability of the biocommercial information depends on the degree of study of items: estimates of stocks of fish with a long life cycle, for which the quantity of the most abundant age groups can be determined by commercial data, are usually more accurate than estimates of stocks of fish with a short life cycle, for which the main and the least-studied part of the population forms the young recruitment. According to expert opinion, the errors of stocks of fish with a long life cycle are usually not greater than 30–60% and more, while the errors of stocks of fish with a short life cycle, as a rule, do not exceed 50–100% (opinion of experts of VNIRO, personal communication). Later on it is assumed that, regarding the population on which an acoustic survey is designed, the error in biocommercial estimate of the stock ε_b is known.

As shown in the previous section, the expression for the resulting error of acoustic estimates of the stock can be presented in the following form:

$$\varepsilon_{bias} = \sqrt{\varepsilon_o^2 + \varepsilon_m^2 + \varepsilon_t^2 + \varepsilon_a^2} \quad = \sqrt{\left(D\nu\right)^4 / S^2 + \varepsilon_m^2 + \varepsilon_t^2 + \varepsilon_a^2} \qquad (7.19)$$

In accordance with formula (7.19), the error of an acoustic estimate depends on the distance between transects; therefore, the degree of decrease of losses, inflicted by errors of design, is also a function of this distance.

It follows from expressions (7.17) and (7.18) that the value of the economic efficiency, received as a result of carrying out one survey, is determined from the formula

$$EF = WKP_1 \left[\frac{t - t_1}{1 + \varepsilon_{bias}} - \frac{t - t_1}{1 + \varepsilon_b} + t_1 \left(\varepsilon_b - \varepsilon_{bias} \right) \right] - \frac{C_1}{v_{vess}} \; (1 + k) \; (1 + L) \qquad (7.20)$$

where ε_{bias} is calculated from expression (7.19).

Relation (7.19) expresses the expected economic efficiency of an acoustic survey designed due to decreasing losses connected to insufficient accuracy of the information received on commercial resources in a region of work. It follows from this relation that, by increasing the volume of a survey, the decrease of such losses can be considerable. However, this makes sense only in the case when the increased survey cost is compensated for by an expected decrease of economic losses (EL) because of the overestimation of the stock. The distance between transects, with which the expected economic efficiency is maximal, is optimal and should be taken as a basis for designing the grid of transects of an acoustic survey.

Let us consider the results of calculation of economic expenses EE, return ER, and efficiency EF of an acoustic survey depending on the distance between transects on the example of the Arctic-Norwegian cod population. The average duration of the life of cod is t = 15 years. The area of the region under study is S = 70,000 miles^2. The coefficient of variation of density values is $\nu = 3.0$. The error of the acoustic method of the density estimation is $\varepsilon_m = 30\%$. The error because of the incorrect choice of initiation of the survey is $\varepsilon_t = 10\%$. The error of the asynchronous character of measurements is $\varepsilon = 20\%$. The error of biocommercial estimates of the stock is $\varepsilon_b = 60\ \%$. The stock is W = 2.0 million tons. The coefficient of commercial withdrawal is K = 20%. The profit per ton of marine production is P_1 = \$80/ton. The extension of passages from the vessel base to the survey region and back is L = 400 miles. The cruising speed of the vessel is $v_{vess} = 8.0$ knots. The coefficient taking into account the time expenses for a force majeure is k = 10%. The cost of exploitation of a vessel per day is C_1 = \$7000/day.

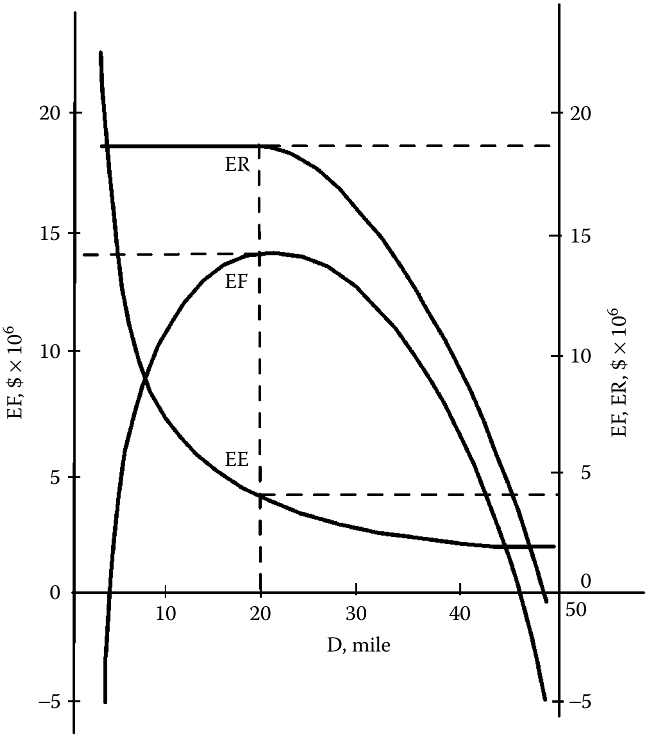

FIGURE 7.9 Dependence of economic indices of the acoustic survey on the distance between transects.

Calculated for this example, the graphs of dependences of EE, ER, and EF on the distance between transect are given in Figure 7.9. It follows from the graphs that with decreasing the distance between transects to D = 20 miles, the economic efficiency of a survey of the cod population increases to the maximal value of EF = $14.6 million. In this case, the expenses for carrying out a survey are EE = $4.0 million and the economic return is ER = $18.4 million. With a further condensation of the grid of transects, the value of economic efficiency falls to negative values, when carrying out an acoustic survey would be unjustified. It is seen from the figure that a survey is only justified under the condition that $3.0 < D < 46$ miles.

It should be noted that the method considered for calculating the economic efficiency of an acoustic survey is a first attempt at elaborating the solution of this problem.* It is understood that experts' estimates of the accuracy of biocommercial data and of the influence of the degree of over-catch on the value of catch in years to come only allow for arriving at very tentative economic estimates.

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* Analogously, it is possible to solve the problem of estimating the economic efficiency of fisheries-acoustic surveys, which are considered in the next chapter.

For detailed elaboration and development of the method of estimating the economic efficiency of surveys, it is necessary to improve the methods of determining the biocommercial estimation of the stock and to discover quantitative dependences of the impact of fisheries and environmental conditions on the value of the subsequent commercial stock and the general allowable catch. In addition, it is necessary to accomplish the complex of investigations, which will allow for connecting the problem of conservation of biological resources with economic parameters of the productivity of a fisheries fleet.

REFERENCES

1. Yudanov, K.I., Efficiency of accounting surveys, *Fisheries*, 4, 48, 1995 (in Russian).
2. Yudanov, K.I., Modes of carrying out multidisciplinary accounting survey, *Fisheries*, 4, 42, 1997 (in Russian).
3. Yudanov, K.I., Ecosystem control of biological resources with the help of accounting surveys, *Fisheries*, 3, 28, 2000 (in Russian).
4. Kalikhman, I., Walline, P., and Gophen, M., Simultaneous patterns of temperature, oxygen, zooplankton and fish distribution in Lake Kinneret, Israel, *Freshwater Biology*, 28, 337, 1992.
5. Yudanov, K.I., Kalikhman, I.L., and Tesler, W.D., *Manual of Acoustic Surveys*, VNIRO, Moscow, 124, 1984 (in Russian).
6. MacLennan, D.N. and Simmonds, E.J., *Fisheries Acoustics*, Chapman & Hall, London, 325, 1992.
7. Kalikhman, I., Patchy distribution fields: An interleaved survey design and reconstruction adequacy, *Environmental Monitoring and Assessment*, 110(1–3), 203, 2005.
8. Kalikhman, I., Patchy distribution fields: Sampling distance unit of an interleaved survey and reconstruction adequacy, *Environmental Monitoring and Assessment*, 119(1–3), 1, 2006.
9. Gandin, L.S., *Objective Analysis of Meteorological Fields*. Translated from Russian by IPST staff, Hardin, R., Ed., Keter Press, Jerusalem, 242, 1965.
10. Stull, R.B., *An Introduction to Boundary Layer Meteorology*, Kluwer Academic Publishers, Dordrecht/Boston/London, 666, 1988, 1989, 1991, 1993.
11. Johannesson, K.A. and Mitson, R.B., *Fisheries Acoustics. A Practical Manual for Aquatic Biomass Estimation*, FAO Fisheries Technical Paper 240. FAO, Rome, 1983, 249.
12. Kizner, Z.I., Optimization of fisheries surveys, *Oceanology*, 29(2), 239, 1989 (translated from Russian).
13. Papoulis, A., *Probability, Random Variables and Stochastic Processes*, McGraw-Hill, New York, 583, 1965.
14. Kalikhman, I.L., Kizner, Z.I., Zaripov, B.R., and Tesler, W.D., Choosing distance between acoustic survey tracks, in Scientific Committee for the Conservation of Antarctic Marine Living Resources, Selected Scientific Papers, Hobart, Australia, V/BG/24, 152, 1986.
15. Kalikhman, I.L., Correcting distance between acoustic survey tracks, in Progress in Fisheries Acoustics, an Underwater Acoustic Group Conference Held at MAFF Fisheries Laboratory, Lowestoft, England, 21/22 March 1989, *Proceedings of the Institute of Acoustics*, 11(3), 212, 1989.

16. Greene, C.H. and Landry, M.R., Patterns of prey selection in the cruising calanoid predator *Euchaeta elongata*, *Ecology*, 66(5), 1408, 1985.
17. Rose, G.A. and Leggett, W., The importance of scale to predator-prey spatial correlations: an example of Atlantic fishes. *Ecology*, 71(1), 33, 1990.
18. Brandt, S.B., Mason, D.M., Patrick, E.V., Argyle, R.L., Wells, L., Unger, P.A., and Stewart, D.J., Acoustic measures of the abundance and size of pelagic planktivores in Lake Michigan, *Canadian Journal of Fisheries and Aquatic Science*, 48(5), 894, 1991.
19. Rudstam, L.G., Lathrop, R.C., and Carpenter, S.R., The rise and fall of a dominant planktivore: direct and indirect effects on zooplankton, *Ecology*, 74(2), 303, 1993.
20. Swartzman, G., Brodeur, R., Napp, J., Walsh, D., Hewitt, R., Demer, D., Hunt, G., and Logerwell, E., Relating spatial distributions of acoustically determined patches of fish and plankton: Data viewing, image analysis, and spatial proximity, *Canadian Journal of Fisheries and Aquatic Science*, 56(1), 188, 1999.
21. Kalikhman, I. and Ostrovsky, I., Patchy distribution fields: Survey design and adequacy of reconstruction, *ICES Journal of Marine Science*, 54, 809, 1997.
22. Kalikhman, I., Patchy distribution fields: sampling distance unit and reconstruction adequacy, *ICES Journal of Marine Science*, 58, 1184, 2001.
23. Kalikhman, I., Patchy distribution fields: A zigzag survey design and reconstruction adequacy, *Environmental Monitoring and Assessment*, 76, 275, 2002.
24. Kalikhman, I., Patchy distribution fields: Sampling distance unit of a zigzag survey and reconstruction adequacy, *Environmental Monitoring and Assessment*, 80(1), 1, 2002.
25. Kalikhman, I., Patchy distribution fields: Acoustic survey design and reconstruction adequacy, in *Environmental Monitoring*, Wiersma, G.B., Ed., CRC Press, Boca Raton, 465, 2004.
26. Kizner, Z.I., Tesler, W.D., and Zaripov, B.R., *Methodological Recommendations on Mathematical Simulation of Commercial Concentrations and Treatment of Survey Data with Computers*, VNIRO, Moscow, 44, 1983 (in Russian).
27. Zaripov, B.R., Kizner, Z.I., and Tesler, W.D., The analysis of methods used in the treatment of data obtained in echo surveys by means of a mathematical model of moving fish aggregations, in Scientific Proceedings of All-Union Research Institute of Marine Fisheries and Oceanography (VNIRO), series "Fishery Acoustic Problems," Yudanov, K.I., Kalikhman, I.L., Shabalin, V.N., Eds., VNIRO, Moscow, 25, 1983 (in Russian).
28. Williamson, N.T., Effect of serial correlation on precision of fish abundance estimates derived from quantitative echo sounder survey, BIOMASS, *Acoustic Krill Estimation Working Party News*, 2, 16, 1980.
29. Yudanov, K.I., *Interpretation of Echograms of Hydroacoustic Fish-Finding Instruments*, Vilim, E., Trans., Keter Press, Jerusalem, 101, 1971.
30. Croxton, F.E., Cowden, D.J., and Klein, S., *Applied General Statistics*, Sir Isaac Pitman & Sons, London, 754, 1968.
31. Greene, C.H., Wiebe, P.H., and Burczinski, J., Analysing distribution of zooplankton and micronecton using high-frequency, dual-beam acoustics, in Progress in Fisheries Acoustics, an Underwater Acoustic Group Conference Held at MAFF Fisheries Laboratory, Lowestoft, England, 21/22 March 1989, *Proceedings of the Institute of Acoustics*, 11(3), 44, 1989.
32. Stanton, T.K., Sound scattering by zooplankton, in Developments in Fisheries Acoustics. A Symposium Held in Seattle, 22–26 June 1987, Karp, W.A., Ed., *Rapports et Proces-Verbaux des Reunions*, 189, 353, 1990.

33. Dommasnes, A. and Roettingen, I., Acoustic stock measurements of the Barents Sea capelin 1972–1984, A review in Proceedings of the Soviet-Norwegian Symposium on the Barents Sea capelin (*Mallotus villosus*), Gjoesaeter, H., Ed., Institute of Marine Research, Bergen, Norway, 45, 1985.
34. Yudanov, K.I., Detection and quantitative estimation of krill concentrations by acoustic instruments, in *Selected Scientific Papers*, Commission for the Conservation of Antarctic Marine Living Resources, Hobart, Australia, 17, 1986.
35. Kalikhman, I., Ostrovsky, I., Walline, P., Gophen, M., and Yacobi, Y.Z., Distribution fields for aquatic ecosystem components: Method of identification of correlation zones, *Freshwater Biology*, 34, 317, 1995.
36. Kalikhman, I., Distribution fields for aquatic ecosystem components: Determination of significance of correlation zones, *Hydrobiologia*, 400, 1, 1999.
37. Kalikhman, I., Yacobi, Y.Z., and Gophen, M., Distribution fields for aquatic ecosystem components: Method of optimization of correlation zones, *ICES Journal of Marine Science*, 60(1), 1, 2003.
38. Kalikhman, I.L., Yudanov, K.I., Borisov, V.M., and Tesler, W.D., An approach to estimating the economic efficiency of acoustic surveys, in Progress in Fisheries Acoustics, an Underwater Acoustic Group Conference Held at MAFF Fisheries Laboratory, Lowestoft, England, 21/22 March 1989, *Proceedings of the Institute of Acoustics*, 11(3), 216, 1989.

8 Fisheries-Acoustic Surveys

Under modern conditions, expensive acoustic surveys for the control of biological resources are carried out, first of all, in international regions. Acoustic surveys in international regions are usually conducted as joint efforts by experts from different countries on several research vessels according to the standard method. Acoustic surveys are also undertaken in national commercial zones in separate cases, for instance, in anomalous years when the ordinary life cycle of commercial fish has been broken under a very strained, close to critical, state of the stocks.

For regularly controlling resources of main commercial items in national waters, it is necessary to carry out a great number of accounting surveys. It is clear that conducting numerous acoustic surveys is unrealistic because of their high cost. A solution to this problem is possible through applying so-called fisheries-acoustic surveys.[1]

It will be shown in the present chapter that the high profit and operability of regular fisheries-acoustic surveys provides the possibility of not only quickly estimating resources and fishing conditions in places of operation of a commercial fleet, but also of carrying out a great volume of complex investigations during the entire season.

The possibility of studying the variability of natural processes in space and time will appear, as well as developing ecological investigations of interrelation, and many other things. The impossibility of conducting intensive ecological investigations, up to now, has impeded a profound development of questions of commercial forecasting. Only economically profitable, regular fisheries-acoustic surveys will allow the speeding up of this process.

8.1 THE ESSENCE OF FISHERIES-ACOUSTIC SURVEYS

It is possible to estimate the state of resources and fishing conditions in a region of commercial fleet operation by catches. Using data of numerous catches of commercial vessels over a vast water area is equivalent to carrying out a trawling survey. However, from data on catches, it is possible to form only a tentative idea about the fish distribution by area and depth or about its biomass as a whole.

To produce more accurate estimates of commercial resources and fishing conditions, it is necessary to use not only the information on catches of commercial vessels but also data from acoustic observations. The density, commercial significance, and biomass of biological concentrations are determined applying this information with the help of fisheries-acoustic surveys.

In short, the essence of fisheries-acoustic surveys consists of the following: in contrast to acoustic or trawling surveys, which are possible to conduct in any water area, fisheries-acoustic surveys are only carried out in regions of an operating commercial fleet. Beginning a fisheries-acoustic survey on a research vessel, control transects are first carried out in places of commercial fleet operation; on these transects, coefficients characterizing the catching ability of commercial trawls are determined.[2]

Using the coefficients received on control transects, the recalculation of catches of commercial vessels into values of area density (in tons/mile^2) is accomplished using the following formula[3]:

$$\rho_s = \frac{3.4 \times 10^6 Q L_{vert}}{K_Q K_{vert} W_{trawl}} \tag{8.1}$$

where Q is the average catch of a commercial trawl, tons/hour; L_{vert} is the vertical opening of a trawl, m; K_Q is the coefficient of catching ability of a trawl; K_{vert} is the coefficient of vertical embrace of concentrations; and W_{trawl} is the commercial productivity of a trawl complex, m^3/hour.

The commercial or technical productivity of the trawl complex used is numerically equal to the volume of a water space, fished by a gear per unit of time.[4] Regarding a known type of trawl, the value W_{trawl} can be determined from the reference book of trawling complexes (e.g., Reference 5).

The coefficient of catching ability of a trawl is the ratio of mass of fish caught to the total biomass in the volume of a space dragged by a trawl. The value of the coefficient of catching ability K_Q depends on many various factors; among them, the correctness of using the fishing gear, the manufacturing quality of a trawl, and the mode of operation. Taking into account the peculiarities of the fish behavior, the knowledge of maneuver, and so on, plays a significant role. Therefore, in our calculations, it is expedient to use an average characteristic of the catching ability of trawls, which takes place in working regions during the studied period.

If the coefficient of catching ability of a trawl K_Q is unknown, its average value is determined based on fishing of concentrations situated within the water column and the acoustic quantitative estimation of the density of these concentrations. The following formula is used for calculating the coefficient of catching ability[4]:

$$K_Q = \frac{3.4 \times 10^6 Q h_{int}}{W_{trawl} \rho_{int}} \tag{8.2}$$

where h_{int} is the thickness of a layer of integration equal to L_{vert} and ρ_{int} is the area concentration density by integrator readings.

From a fisheries report, catches of commercial vessels are chosen, which were made near acoustic measurements of the concentration density within a layer of fisheries; data of control fishing from a research vessel are also used. These catches are averaged and reduced to one hour of trawling. The area density ρ_{int} is found acoustically using the standard method. The horizon of integration is set on the depth of registering concentrations and the thickness of the layer of integration should correspond to the vertical opening of a trawl.

In determining the area density of commercial concentrations by catches, it is necessary to take into account that, in the overwhelming majority of cases, the vertical extension of concentrations does not coincide with the vertical opening of trawls. The layer of catching can be either more or less than the thickness of concentrations. Therefore, to correct the mentioned lack of correspondence, the coefficient of the vertical embrace of concentrations K_{vert} is introduced; this factor ensures the transition from an area concentration density within the layer of catching ρ_{int} to a whole area concentration density by its entire thickness ρ_s. The value of this coefficient is determined from the following relation:

$$K_{vert} = \rho_{int}/\rho_s \tag{8.3}$$

As follows from formulas (8.2) and (8.3), acoustic measurements of values ρ_{int} and ρ_s are required in order to determine the coefficients K_Q and K_{vert}. These measurements are carried out on control transects at places of operation of a fishing fleet. Acoustic control transects should be laid through the main parts of concentrations caught. With a great congestion of fisheries vessels, in order not to disturb each other, parallel courses are used; therefore, the directions of control transects should coincide with the general courses of movement of commercial vessels. The unit of sampling distance on control transects is usually taken equal to the average extension of one hour of trawling of commercial vessels.

Example

It is established in a region of trawling for blue whiting that the optimal horizon of fishing with the vertical opening of a trawl equal to $L_{vert} = h_{int} = 60$ m corresponds to the depths of 330–390 m. Area concentration densities, measured on control transects within the layer of fishing and throughout the whole thickness, are equal to $\rho_{int} = 160$ tons/mile^2 and $\rho_s = 230$ tons/mile^2. Then from relation (8.3), the correcting factor $K_{vert} = 160/230 = 0.7$.

In the fisheries region, vessels of large tonnage are using a trawl, the technical productivity of which, with a trawling speed of 4.5 knots, is equal to $W_{trawl} = 2.5 \times 10^7$ m^3/hour. The average catch per hour of trawling $Q = 4.0$ tons. The coefficient of catching ability from formula (8.2) is equal, in this case, to:

$$K_Q = \frac{3.4 \times 10^6 \times 4 \times 60}{2.5 \times 10^7 \times 160} = 0.2$$

Having determined the coefficients K_Q and K_{vert} on control transects, it is possible to recalculate the catches at places of operation of commercial vessels from formula (8.1) into values of area density of concentrations caught ρ_s. Besides K_Q and K_{vert}, initial information for such calculations includes catches Q, the vertical opening L_{vert} and the technical productivity W_{trawl} of trawls with regard to each fishing vessel; these data are available from commercial councils and reports. The values of area density received are plotted on a plane table, isolines are drawn and the biomass is estimated.

In order to solve operative problems connected to the rational fisheries design and fleet placement, it is not enough to study only the dynamics of biomass, with account taken of oceanographic factors. It is important to have a clear idea of the distribution of concentrations from the point of view of their commercial significance in various sections of a region. The commercial significance of concentrations detected by acoustic instruments is characterized by the value of a possible catch per hour of trawling these concentrations. Data on commercial significance are produced as a result of treatment of the acoustic information and the operation of commercial vessels.

The commercial significance is tentatively determined from acoustic data (in tons/hour) by the following formula:[3]

$$Q = 2.9 \times 10^{7} K_Q W_{trawl} \rho_{int} / h_{int} \tag{8.4}$$

During fisheries in a certain region, the values of the technical productivity W_{trawl}, the layer integration thickness h_{int}, and the trawl catching ability coefficient K_Q are usually comparatively constant; therefore, their averaged values are used. Only the value of the concentration density ρ_{int} varies within great limits. Taking this circumstance into account, it is possible to determine the commercial significance of concentrations from the following simplified relation:

$$Q = C_{cs} M_1 \tag{8.5}$$

where $C_{cs} = 2.9 \times 10^{-7} K_Q W_{trawl} C / h_{int}$, tons/hour; C is the value of the scale of an integrator, which is determined by the standard method; and M_1 are integrator readings, reduced to one ping along an interval of one hour of trawling.

The value M_1 is obtained through dividing readings of an integrator by the number of pings of an echo sounder for one hour of trawling.

The practice of surveys shows that, for determining the commercial significance of concentrations by acoustic data with the use of formula (8.5), executors of high enough qualification are required, able to carry out the acoustic calibration of the equipment and the measurement of the coefficient of catching ability of trawls. The commercial significance by acoustic data is usually determined with regard to the most appropriate trawling complex for a given region, using for this determination corresponding values of K_Q, ρ_{int}, and W_{trawl}.

The commercial significance of concentrations is also calculated from catches of commercial vessels, reducing them to the main trawling complex. The following relation is used in calculations:[3]

$$Q = Q' \frac{W_{trawl} K_Q}{W'_{trawl} K'_Q} \tag{8.6}$$

where Q, K_Q, and W_{trawl} correspond to trawling complexes, the most appropriate for a given commercial region; and Q′, K'_Q, and W'_{trawl} correspond to other complexes.

Unifying data on commercial significance, received acoustically and from catches, a plane table of the distribution of concentration is plotted. On such a plane table, an obvious picture of the distribution of concentrations by their commercial significance is developed; the fisheries sections are clearly seen.

The analysis of a series of fisheries-acoustic surveys on a research vessel also allows for determining the character and direction of main movements of concentrations, estimating changes in the fish distribution by water area and depth, and specifying in due course dates of the possible decrease of catches down to a critical level; after such a date, fisheries are no longer profitable and changes in the deployment of the fleet are required.

It is possible to regard the above mentioned considerations as a basis for the method of fisheries-acoustic surveys on research vessels. The suggested type of investigations of commercial regions possesses great advantages when compared to acoustic and trawling surveys. An advantage of fisheries-acoustic surveys is their high operability. Such surveys can be accomplished within a very short time; some asynchronous character of measurements does not, practically, distort plane tables of the distribution of fish concentrations.

In contrast to acoustic and trawling surveys, in carrying out fisheries-acoustic ones, it is only necessary to accomplish several control transects near the group of commercial vessels and along the periphery. Acoustic and fisheries information, collected and appropriately treated, allows rapid reception of a picture of the distribution of concentrations by their density and commercial significance in a fisheries region. An especially great gain in time is received in studying bottom concentrations, as trawling and acoustic surveys, in this case, require a large number of controlled catches by a bottom trawl.

8.2 SURVEYS OF FISHING CONDITIONS

Let us consider questions connected to the tactics and the profit of surveys of fishing conditions.

SURVEY TACTICS

After the arrival of a research vessel at a region of work, it is necessary to first familiarize oneself with radio transmissions of fishing conditions, according to which a map of deployment of commercial vessels and their catches is plotted. Such a map gives an idea about the borders of a region, the deployment and the number of fisheries vessels, as well as about the commercial significance of concentrations caught by them.

Control transects are carried out near the region of operating fishery vessels before the beginning of surveys of fishing conditions for estimating the density and commercial significance of concentrations. The coefficient of catching ability of trawls of fishery vessels and that of the vertical embrace of concentrations caught are determined on control transects by the acoustic method. Knowing these coefficients, the recalculation of catches of fishery vessels into the values of density (from formula 8.1) and commercial significance (from formula 8.4) is made; plane tables of the distribution of mentioned parameters are drawn. Oceanographic stations for measuring the main environmental parameters and control fisheries for ichthyologic samples are made on control transects at places of abrupt changes of the character of distribution of fish concentrations. The direction and speed of the fish and currents are also measured. The species, size, age, sex, and weight composition of concentrations, as well as the stage of maturity, the fattiness, the character of feeding, the stomach content, and other indexes, are determined from ichthyologic samples.

An oceanographic transect is carried out for specifying forecasted environmental conditions in a region under survey and for connecting them to the distribution and biological state of fish. A transect should pass through places which characterize most fully the conditions of temperature of a given region. A characteristic example of such a standard section is the well-known transect "Kolsky meridian."

Regular observations on a standard oceanographic transect allow for receiving valuable material for studying the impact of environmental conditions on the development of biological items. These observations give an idea of the influence of temperature conditions on the harvest of generations of fish, on the peculiarities of their distribution, the maturity, the fattiness, and so on. All the main sources of information are used to specify oceanographic conditions: radio transmissions, a weather forecast, data of meteorological services, results of measurements carried out on vessels situated in a region under study, data of remote sensing of a surface ocean layer with the help of satellites, and so on.

The control of fishing conditions must encompass the main parts of a region and their periphery along the side of the suggested movement of fish concentrations. Acoustic transects and oceanographic stations at the periphery of a commercial region are made taking into account the intersection of the main streams of currents and fisheries isobaths. Control catches and oceanographic stations are also carried out at places of changes of the character of concentrations registered by acoustic instruments.

The periodicity of conducting surveys at regions of operation of a fisheries fleet is determined by the degree of variability of fishing conditions, which depends on physical and synoptic conditions, as well as the biological state of the fish. It is necessary to carry out fisheries-acoustic surveys and passing oceanographic and biological observations the most frequently within so-called crucial periods, when abrupt changes in the fish distribution occur; for instance, during the mass fish migrations to spawning or wintering grounds, during abrupt changes of weather conditions, as well as along their routes of migration to traditional places of formation of concentrations, and so on. It is possible to undertake rare surveys under stable fishing conditions.

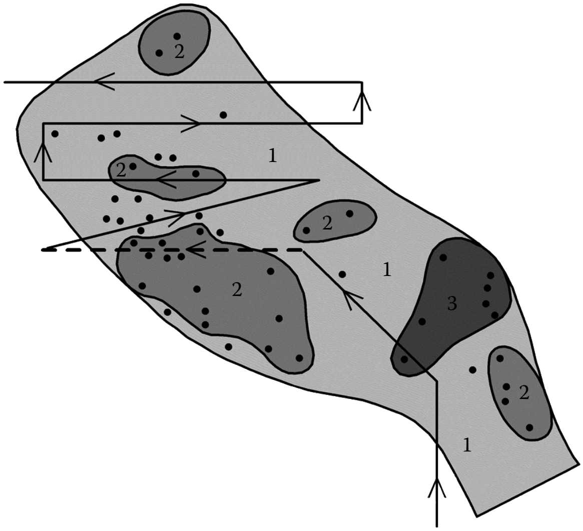

FIGURE 8.1 April 1987, North Atlantic. The plane table of the distribution of blue whiting concentrations by their commercial significance: 1, Q < 5.0 tons/hour; 2, 5.0 < Q < 10 tons/hour; 3, Q > 10 tons/hour. Points show the locations of trawling; dashed line indicates the control transect (Bondarenko, V.M., personal communication).

If a sufficient number of vessels work in a fisheries region, for surveying and controlling fishing conditions, plane tables of the distribution of commercial significance of fish concentrations are drawn first. An example of such a plane table is given in Figure 8.1.[6] A regular comparison of such plane tables provides an opportunity for correcting the location of fisheries vessels and determining their optimal number in a region.

Having revealed the tendencies in dynamics of distribution of commercial concentrations, it is possible to draw forecasted plane tables indicating the directions of movement of concentrations and possible catches. The synoptic forecast for a given region, characteristics of the medium, and the biological state of commercial items are taken into account in compiling such plane tables. Practice shows that such short-term forecasts of fishing conditions may prove to be correct with some working experience in a specific region.

In the estimation of fishing conditions on research vessels, it is expedient to carry out measurements of the value of commercial significance by several channels of integration at different depths. The results of acoustic measurements allow plotting graphs of the distribution of commercial significance by depth. Such graphs provide an opportunity to select optimal horizons of fishing and the opening of trawls.

The fish distribution by depth often undergoes great changes with various physical conditions of the water medium, with the different biological states of items and so on. Considerable changes in the distribution of concentrations occur during their daily vertical migrations. This is, in turn, reflected on the volume concentration density and, consequently, on their commercial significance.

The graphs of the distribution of commercial significance of blue whiting concentrations in the North Atlantic by depth during various times of the day are given in Figure 8.2 as an example. Five channels were simultaneously used to measure the commercial significance. The thickness of the layers of integration in each channel was equal to the vertical opening of the trawl, 50 m. The location of the channels by depth was set with the overlapping equal to 25 m. As seen from the graphs, the most productive layer for the fisheries was situated, during the daytime, within the limits from 335 to 385 m; at night, from 250 to 300 m.

Thus, the variation of commercial significance is not obligatorily connected to changes of the biomass in a region, as it strongly depends on the character of the fish distribution. For example, with mass fish coming to a region within the period of migrations or with fish localizing during the spawn, concentrations condense and their commercial significance abruptly grows; respectively, catches increase. In contrast, under fish diffusion by great area or depth within the period of active feeding, even with considerable general biomass, the decrease in commercial significance of concentrations may not ensure a daily quota of catch. In this case, the fisheries should be displaced or reorganized with alternative fishing gear; for example, the transition from trawls to drift nets should be made.

If a noticeable increase of dimensions of concentrations and catches is observed during the control of fishing conditions, the conclusion can be made that a mass fish migration to a region has begun. In this case, in addition to determining the com-

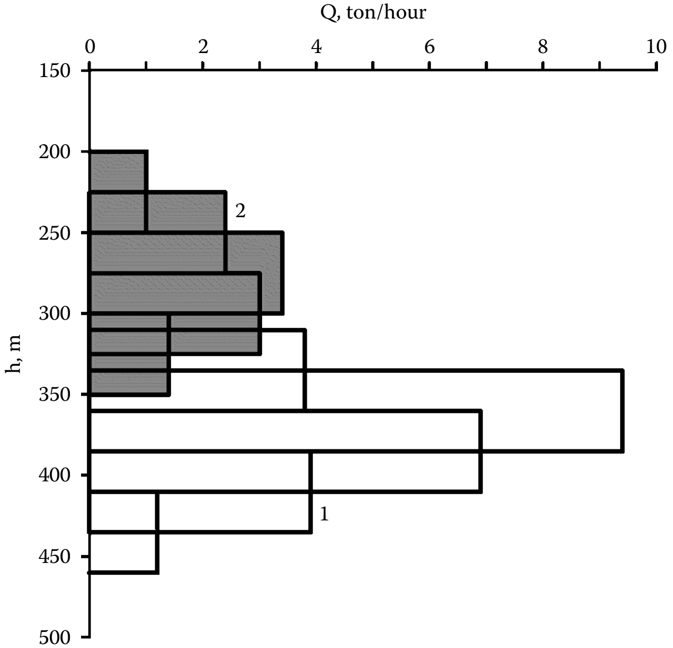

FIGURE 8.2 The distribution of commercial significance of blue whiting concentrations by depth: 1, during the day; 2, at night (Ermolchev, V.A., personal communication).

mercial significance, it is expedient to measure the concentration density by the standard method, to draw plane tables of the density distribution, and to estimate the biomass.

Accomplishing a series of surveys of fishing conditions with estimation of the concentration biomass provides the possibility of observing, dynamically, the changes of the density, of studying natural regularities of the formation, stable distribution, and disintegration of concentrations; this, in turn, allows for better orienting oneself as to fishing conditions. It is especially important to follow the dynamics of changes of the total concentration of biomass, the intensity of fish coming to a region or leaving it. Such observation should be conducted during periods of fisheries' fattening, spawning, and wintering concentrations. Under intensive fisheries of concentrations, the variation of their biomass should be determined taking into account the commercial withdrawal.

Carrying out frequent surveys of fishing conditions allows for drawing a graph of changes of the biomass in time. The knowledge of a daily fish catch gives the possibility of determining the coefficient of commercial withdrawal and its rate. The graph of variation of the mentioned values allows for controlling the correspondence of the actual catch to the optimal one.

Biologists establish the optimal value of the coefficient of commercial withdrawal depending on the duration of life and reproductive capability of surveyed fish, on the harvest of generations, on the age composition of a population, and other factors. The value of a catch is ascertained from radio transmissions and commercial reports. The actual value of the coefficient of commercial withdrawal is found by dividing the value of a catch by the biomass of fish concentrations. The coefficient of commercial withdrawal is divided by the duration of a period from the beginning of the commercial season up to the moment of time of accomplishing a survey in order to determine the rate of commercial withdrawal.

EXAMPLE

Two months have passed since the beginning of the commercial season up to the moment of the present survey in the region of fisheries of blue whiting. It is seen from the graph in Figure 8.3 that the value of the total catch is equal to 30,000 tons; the biomass of fish concentrations changed from 870,000 to 900,000 tons; the actual value of the coefficient of commercial withdrawal is about 3%; and the rate of commercial withdrawal is 1.5%.

The optimal value of the coefficient of commercial withdrawal regarding the population of blue whiting is assumed to be equal to 15%; the duration of the fisheries season is 7 months. The corresponding rate of commercial withdrawal is 2.1%. Thus, an under-catch took place within the period from the beginning of the fisheries season to the moment of carrying out the survey.

In addition, the graph of changing of the biomass in a traditional region provides the possibility to correctly choose the time favorable for carrying out a survey of the state of stocks, when most commercial resources gather in the same region. The dynamics of fish arrival in a region depends on environmental conditions and the

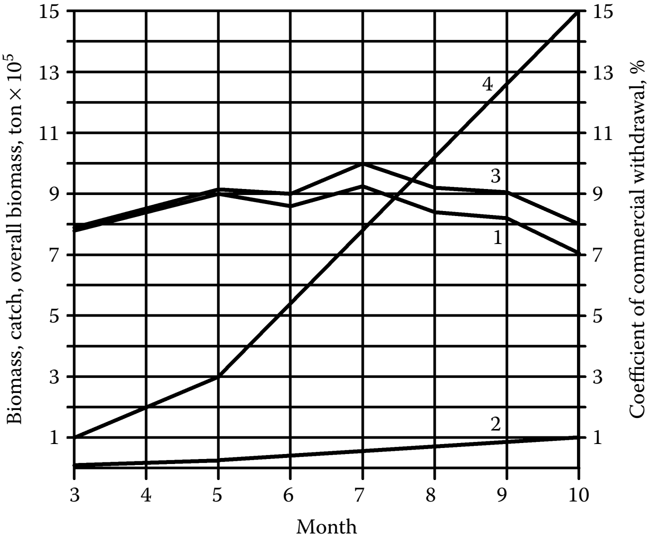

FIGURE 8.3 The fisheries of blue whiting in the Norway Sea. Diagrams of the changes in the following parameters during the fishing season: 1, biomass of fish concentrations; 2, catch; 3, overall biomass and catch; 4, coefficient of commercial withdrawal.

biological state of items; it may change from year to year in each season. Therefore, for choosing more exactly the time of maximal fish arrival, and then the time of conducting a survey of the state of stocks, as the fish arrival increases, it is necessary to accomplish more frequent acoustic measurements of the concentration density, oceanographic stations, and ichthyologic samples.

Regarding the graph of the previous example (Figure 8.3), the maximum growth of the biomass corresponds to the beginning of July; a survey of the state of stocks of blue whiting should be carried out at exactly this time.

SURVEY PROFIT

The method of fisheries-acoustic surveys of fishing conditions was tested on scientific vessels on several expeditions in different basins (see, for example, Reference 6). Carrying out such surveys convincingly proved their high efficiency and profitability when controlling fishing conditions; this established a great interest by the fishermen in receiving such information when it is used to serve fisheries vessels by providing operative and forecasting data.

Fisheries-acoustic surveys proved to be very efficient in preparing short-term forecasts of fishing conditions. Due to such surveys, short-term forecasts of fishing conditions proved to be correct in about 100% of the cases.

As a result of carrying out fisheries-acoustic surveys, it was established that the increase of productivity of commercial vessels due to the use of recommendations and forecasts fully justified the conduction of these works on research vessels. Thus, experts' estimates in the southeast Atlantic showed that regular transmissions of the forecasting plane tables from the research ship increased the catches of a great number of commercial vessels by more than 10% on the average; i.e., the cost of exploitation of the research ship was more than compensated.

Due to the recovered cost of exploitation of a research vessel, carrying out surveys of fishing conditions makes it possible to estimate the state of biological resources and to conduct a great volume of multidisciplinary investigations. Additionally, observations of the variation of distribution, biomass, and quantity of fish concentrations in connection with environmental parameters practically do not demand additional temporal and material expenses, as they are conducted in parallel with surveys of fishing conditions.

Thus, the long-term exploitation of a research vessel in the regime of repayment of surveys of fishing conditions can be profitable in carrying out surveys of fisheries resources, as well as for studying the dynamics of ecological interrelations. It should once more be emphasized that the profitable work of a scientific vessel is only possible under the condition that fisheries-acoustic surveys are organized during the whole commercial season.

It should also be noted that the regular control and forecast of fishing conditions, ensuring the efficient operation of a fisheries fleet, is not only a necessary condition of the profitable use of a research vessel, but also a service of scientists to managers of fisheries for the help in receiving additional information, important for the analysis of the state of commercial resources.* The mentioned reasons explain the necessity of carrying out a great volume of studies connected to the estimation of fishing conditions.

8.3 SURVEYS OF COMMERCIAL RESOURCES

Let us consider the choice of the time for the initiation of surveys, as well as questions connected to its tactics.

Choice of the Time for the Survey Initiation

It was shown in Section 7.1 that the time for the initiation of a survey of commercial resources should correspond to the maximal fish arrival to a region surveyed. The practice of fisheries-acoustic surveys shows that a series of surveys of fishing conditions are required in order to correctly determine the moment of maximal fish arrival. Carrying out frequent surveys of fishing conditions before the initiation of a survey of commercial resources allows for following a regularity of the change in the fish biomass in a commercial region. This regularity enables correctly choosing the favorable time for conducting a survey of commercial resources, when most of the fisheries stock gathers in this region.

Because of the great rate of increasing biomass and of the short period of existence of maximal concentrations, it is necessary to initiate a survey for estimating the state of stocks immediately after the end of the abrupt increase of the biomass;

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* The experience of marine fisheries shows that the operative management of fisheries is required for efficient work of a commercial fleet in national waters.

i.e., near its maximum. If the maximum period is rather long, a survey should be carried out within the middle of this period, up until no decrease in the biomass has begun.

The dynamics of the fish migration to a region depends on conditions of the medium and the biological state of items, and it may change from year to year in each season. Therefore, to determine more exactly the time of the maximal fish arrival, and then the time to accomplish a survey of resources, it is necessary, as the fish migration increases, to carry out more fisheries-acoustic estimates of the density, oceanographic stations, and ichthyologic samples.

SURVEY TACTICS

After establishing the time for the survey initiation, the carrying out of a survey itself starts. In conducting a survey, most attention is paid to the reception of a more adequate picture of the distribution and the most accurate estimates of fish quantity and biomass in a region surveyed. Oceanographic conditions are specified only in a case of extreme necessity.

For estimating the fish state, a survey is usually conducted at the end of the period of fattening, when the majority of a population gathers in a region and fish keep, comparatively stably, within a limited space, forming rather dense concentrations prior to migrating to places of wintering. Surveys within the period of fattening show to what extent the state of commercial resources differ from the critical level.

With a strained state of the stock, the regular control of the quantity of a spawning shoal is especially important. A survey of a spawning shoal is usually carried out during the time of the fish arrival at the spawning grounds, when they form dense local concentrations.

In contrast to a survey of fishing conditions, a much greater number of investigations are conducted in estimating the state of stocks. A survey is conducted on an area encompassed by fisheries, as well as on unstudied parts of the area inside a commercial region and on its periphery, to the side of the suggested motion of concentrations. Control acoustic transects are conducted and the biomass is estimated by catches on those parts of a region where the commercial fleet operates. Additional transects are accomplished between groups of commercial vessels with a very nonuniform distribution of concentrations. An ordinary acoustic survey is carried out on peripheral sections of a commercial region. In these cases, the grid of transects is designed and the biomass is estimated by the standard method (see Chapter 7).

In carrying out a seasonal survey for determining the state of stocks, it is important to estimate the fish quantity by age groups. For this purpose, from results of control catches in different locations of a region under survey, the length and age composition of fish concentrations are determined, as well as "keys"; i.e., relations with the help of which the percentage composition is calculated according to the age in each group. The length composition of concentrations is also determined from readings of the special split-beam acoustic equipment (see Section 5.2). It is possible to continuously observe the histogram of the length composition of a concentration registered by instrument along the course of a vessel on the display of such equipment.

At places of noticeable changes of the length composition, readings of the percentage composition of length groups are taken from the histogram; these readings are recalculated with the help of keys into age relations. Such data of age relations, received through control catches and acoustic measurements, are used for plotting the distribution of fish concentrations regarding each age group; the quantity and biomass according to the age are estimated (see Section 7.2). Determination, with the help of surveys, of the quantity of biomass of commercial fish down to recruits and young, and comparing these data by seasons, allow for calculating the rate of the growth and forecasting the variation of the biomass of fattening and spawning shoals of different species in the coming season.

After finishing a detailed seasonal survey for estimating the state of stocks, all materials of this survey, as well as surveys of fishing conditions carried out just before and after estimating the maximal value of the biomass, are systematized and analyzed. This makes it possible to examine the real state of stocks.

It is possible to consider the maximal value of the biomass, received as a result of a detailed survey, as a control value of the state of resources in a region under investigation. However, the value of the biomass, measured at the maximal fish arrival to a region, does not entirely determine the state of resources; it strongly depends on the character of fish migrations and may change to either side under the impact of environmental conditions. It should be noted that the value of the biomass measured only corresponds to the real commercial resources if there is certainty that a survey encompassed the main part of the population.

In carrying out surveys of resources, besides the biomass, the average value of the density of concentrations and their area are determined. It is known that, with a depressed state of stocks, the density and area of commercial concentrations noticeably decrease. The results of measurements of the parameters of concentrations can be used for forecasting the state of stocks only if they are connected with environmental characteristics.

The comparison of the distribution of the density of fish concentrations and oceanographic characteristics, received as a result of seasonal surveys, provides the possibility of estimating the impact of physical conditions, feeding fields of plankton, currents, and other factors of the medium on the variation of the quantity, biomass, and the routes of fish migrations. Seasonal measurements of the quantity, the area, and the density of fish concentrations make it possible to obtain quantitative variations of these values under various environmental conditions. The analysis of parameters of concentrations and the medium by seasons and years will allow one to judge more accurately the state of resources in commercial regions, to investigate the reasons for the growth or fall of the biomass and to forecast the subsequent changes in stocks.

8.4 ECOLOGICAL SURVEYS

Multidisciplinary surveys have been carried out for many years on numerous marine expeditions in various regions of the World Ocean. Such surveys are also conducted now. Multidisciplinary surveys, including acoustic, ichthyologic, and oceanographic investigations, are intended to study the peculiarities of the distribution of commercial concentrations under the impact of different environmental factors and taking into account the biological state of fish.

The role of conditions of the medium and the physiologic state of fish does not remain constant throughout the various steps of their life cycle. During spawning migration, the role of external conditions gradually decreases and the physiologic state of fish becomes a leading one. The main role with feeding migrations is played by external factors such as food and temperature conditions.

Temperature conditions of water masses influence for the activity of fish to a high degree. The extension, periods, and rate of migrations, as well as the time of formation of concentrations, depend on the temperature regime. The area of fish habitation widens in warm years and narrows in cool years. The routes of migrations and the area of fish distribution are shifted within the period of fattening, wintering, and spawning under an abrupt change of the temperature regime. The rate of changes is considerably more intensive in cool years than it is in warm ones.

Many years of multidisciplinary studies allow, to a great degree, elucidation of the general dependences of the influence of separate environmental factors on the formation and distribution of commercial concentrations of various fish species, based on averaged data. Unfortunately, until now, the detailed peculiarities of formation of fish concentrations have been unyielding to study.

Important for forecasting, many-factored interrelations characterizing favorable conditions for the formation of zones of high biological productivity, as well as the temporal variability of the main factors influencing the formation of concentrations, have been weakly studied. For instance, a detailed study of the degree of the impact of temperature, feeding plankton, and other factors on the formation of commercial concentrations at various steps of the life cycle of fish is required. It is known that the formation of a concentration can be due to fish immigration from other regions, as well as to the concentration of dispersed items.

One of the reasons for the inefficiency of existing methods of carrying out multidisciplinary surveys is the insufficient volume of information on plane tables of distributions of fish concentrations and environmental parameters, received as a result of surveys. This is explained by the small number of oceanographic measurements and imperfections in the treatment of the acoustic information. Therefore, only plane tables characterizing the general picture of the distribution of fish concentrations and environmental parameters have been successfully constructed. Such a situation does not provide the opportunity to study the reasons for changes of the character of fish distribution and behavior under the impact of various factors.

Until recently, the construction of plane tables of fish concentrations was directed at determining the quantity and the biomass, and estimating the distribution of commercial items was a question of minor importance. Plane tables regarding the biomass estimation are constructed by integrator readings averaged over a great interval of the vessel path. Therefore, the picture of the distribution of commercial concentrations is smoothed; it strongly differs from the actual one and is of little use in studying the peculiarities of fields of fish concentrations.

To correct this shortcoming, it is necessary, first of all, to considerably shorten the time interval for measuring the acoustic information, which requires a more complicated data treatment for constructing detailed plane tables of fields of fish concentrations. The necessity of a sharp increase in the number of oceanographic stations and measurements within a comparatively limited amount of time is a difficult task. This problem can only be solved with the help of electronic measurers of environmental parameters operating from a moving vessel.

At present, different firms produce towed carriers of oceanographic sensors (ondulators). Such carriers are towed in a sinusoidal trajectory, alternately coming to the surface and plunging to maximal depths of 100–400 m. Broken and returnable carriers are also produced. Returnable carriers automatically sink to a given depth, and then rise up to the sea surface; after that the cycle is repeated.[7]

A complex of measuring equipment, installed on a towed carrier, allows for receiving aboard a moving vessel, practically continuous transects of corresponding environmental parameters. Towed carriers are rather expensive and bulky for the present. However, taking into account the fast development of towed systems, in the near future they will become available for wide use in ecosystem investigations.

A different method of collecting and treating survey data is also required for the reliable estimation of the distribution of commercial items and environmental parameters. The regime of isolation of gradient zones should serve as a basis for the method of constructing plane tables of the distribution of items and environmental parameters. The development of new principles of detection and registration of such zones is required.

It should, however, be emphasized that the main reason for the failure of existing methods of multidisciplinary surveys consists in the tactics of carrying out the investigations rather than in the methods of collecting and treating data. It was mentioned in Section 7.3 that, in carrying out surveys over a large water area, a dissociation of the collected multidisciplinary information in space and time appears. This dissociation is due to the considerable variability of the distribution of commercial items and environmental parameters in the ocean and to the long duration of expedition works.[8]

As a result of the great dissociation of measured data, their spatial distribution in plane tables is strongly distorted; the noncorrespondence of the location and shape of fields of fish concentrations and oceanographic elements on plane tables to their actual position takes place. This acts negatively on results of studying interrelations of the fish distribution and environmental parameters. For this reason, prolonged multidisciplinary surveys at sea have not provided, as yet, any reliable result in estimation of ecological interrelations.

It is possible to correct such a situation by decreasing the duration of multidisciplinary surveys down to an allowable minimum. As has already been mentioned, a considerable decrease in the duration of surveys can be achieved through the use of a towed oceanographic measuring system. Application of such systems will strongly decrease the time and means necessary for carrying out multidisciplinary surveys, as investigating commercial concentrations by acoustical equipment and measuring environmental parameters by a towed system will be possible, simultaneously, from a moving vessel.

The choice of the minimal required time for investigating a region outlined is considered in Chapter 7 regarding acoustic surveys of commercial concentrations. It was shown in Section 7.1 that the allowable duration of a survey can be calculated from formula (7.3). The task regarding oceanographic investigation may be solved analogously:

$$t_{surv} = \varepsilon_a l_{surv}/v_{par} \tag{8.7}$$

where ε_a is the error because of nonsimultaneity of measurements, l_{surv} is the diameter of the area of a region under investigation, and v_{par} is the speed of process of variability of an investigated parameter.

The speed of processes of variability of oceanographic parameters is directly connected to the mixing of water masses under the impact of currents, meanders, or thermoclines. It is possible to assume the speed of the plankton movement equal to the velocity of currents and other perturbations as it drifts together with water masses. The speed of the variability of temperature and of other parameters of the medium is usually commensurate with the velocity of currents.

As far as studying the variability of environmental parameters in space and time, it will become possible to determine the speed v_{par} and to estimate the time t_{surv} from formula (8.7). For the present, it should be guided by the speed of movement of fish concentrations in determining the allowable duration of a multidisciplinary survey. The speed of fish movement nearly always exceeds the velocity of oceanographic processes.

Rapid multidisciplinary measurements of the density of commercial concentrations and environmental parameters, taking into account the physiological state of fish, will be referred to later on as *ecological surveys*. The main purpose of ecological surveys is to study ecosystem interrelations between the enumerated characteristics. We consider that, at present, there are all the necessary premises for carrying out ecological surveys. According to our opinion, large-scale ecological surveys will receive wide development with time. The results of such regular surveys will allow for raising the level of forecasting of commercial resources.

The main difference between ecological surveys and surveys of resources consists of the fact that the former should ensure the collection of data on dimensions, configuration, and structure of fields of density of fish concentrations and the major environmental parameters having an impact on the distribution of commercial concentrations.

For studying the influence of environmental conditions on the formation of commercial concentrations, it is necessary to control the dimensions and structure of fish concentration, connecting them with corresponding parameters of the medium. Such control should be accomplished in the course of surveys of fishing conditions. To more clearly isolate separate schools inside commercial concentrations, the unit of sampling distance must be made considerably smaller than that taken when surveying stocks. In contrast, the number of oceanographic measurements for connecting environmental conditions to fish concentrations must be much more significant than those made in carrying out surveys of resources.

It is necessary to begin the study of ecological relationships in a region outlined by carrying out a preliminary survey. Plane tables of the distribution of fish concentrations and environmental parameters, drawn as a result of such an ecological survey, will allow examining the situation and correcting a further detailed survey. Gradient zones are plotted on plane tables. Transects of further surveys must intersect gradient zones of fields of fish concentrations, plankton, temperature, and other factors of the medium at different sections of a commercial concentration.

Dimension and structure parameters of fish concentration, the character of stratification of water masses, and the location of frontal zones, where variations of physical parameters are great, should all be taken into account in designing the grid of transects of ecological surveys. Carrying out such surveys provides the possibility to study in detail the impact of different factors of the medium on the formation, distribution, and disintegration of fish concentrations.

Usually, for studying ecological interrelations, investigating an entire region is not required, especially if it is extensive. It is enough to work on one comparatively large fish concentration, recurrently returning to it. The periodicity of carrying out ecological surveys in a region of fishing fleet operation is determined by the temporal variability of processes under study as well as by fishing conditions, which depend on physical, synoptic conditions and the biological state of the fish.

Under stable fishing conditions, multidisciplinary surveys are carried out rarely, when biological analyses indicate noticeable changes in the physiological state of fish, especially before spawning, fattening, or wintering. Fisheries-acoustic surveys of the entire working region of a commercial fleet are carried out rather frequently for collecting operative and forecasting information within the period of active fishing (see the previous section).

It is necessary to frequently conduct ecological surveys within so-called crucial periods, when abrupt variations of physical conditions or the biological state of fish lead to significant changes in their distribution and behavior. Rapid multidisciplinary surveys are completed by fisheries-acoustic investigations within such periods.

With frequent ecological surveys, it is also possible to study the short-term dynamics of processes of variability of fish concentrations and environmental parameters, as well as interrelations between them. As the short-term variability of fish concentrations is connected with synoptic phenomena, it is expedient to carry out series of frequent surveys at the time of unstable weather conditions, when the greatest variations in the item distribution take place. It is necessary to use high-frequency echo sounders for the distinct registration of fish in stormy weather.

An area surveyed can be different depending on the rate of the short-term variability of fields under study. Thus, if processes of variability of the distribution of fish concentrations occur rapidly and abruptly, it is desirable to study them on small, local concentrations with an area not exceeding 100 miles^2, carrying out such micro surveys up to once a day. It is possible to study processes varying slowly and smoothly with the help of series of surveys conducted on comparatively large commercial concentrations.

Ecological surveys undertaken to study interrelations within an ecosystem are especially important. In studying such interrelations, it is necessary to take into account the competition in feeding different species of items, when they play the role of predators or prey in relation to each other; it should also be borne in mind that the intensive exploitation of one of several interacting species can strongly affect the quantity of others.

The accomplishment of rapid multidisciplinary surveys allows for receiving important quantitative characteristics of trophic relations of different fish species. It should be taken into consideration that areas of distributions of predators and prey are often disconnected in space; therefore, to carry out ecological surveys, it is necessary to know periods and dates when areas of distribution of interacting species coincide with each other.

It is possible to study feeding interrelations between species with the help of ecological surveys on mixed fish concentrations and on concentrations of feeding plankton. For instance, one can conduct surveys of local concentrations of Barents Sea capelin, in the proximity to which there are cod feeding on capelin; on mixed concentrations of Baltic herring and cod, when the latter feed on small herring; on dense concentrations of plankton eaten by fish, and so on.

It is possible to study the rate of the fish growth in connection with environmental conditions in a series of rapid multidisciplinary surveys carried out successively. It is known that optimal temperature conditions favorably affect food consumption, increase the speed of growth, and make more active the sexual maturity of fish. Under abundant feeding and favorable temperature conditions, fish at an earlier age become sexually mature and replenish a spawning shoal. Therefore, with the help of surveys, studying the growth rate according to the age in connection to natural conditions has a significant importance in estimating stocks of sexually mature or immature fish.

Ecological surveys are also required to study the negative affect of the medium pollution on fish stocks. For this purpose, surveys are carried out near centers of pollution and on their periphery for elucidating the damage caused. Surveys are also conducted after eliminating the pollution to control the ecological equilibrium broken, to estimate the quantity of plankton, fish, marine mammals, or birds.

It should be noted, in conclusion, that suggested multidisciplinary ecological investigations will become widely developed only under the inculcation of fisheries-acoustic surveys, the profitability of which will allow for conducting a great volume of rapid ecological studies from a research vessel over a long period of time.

8.5 ANALYSIS AND APPLICATION OF SURVEY RESULTS

The fish distribution throughout an investigated area is established as a result of fisheries-acoustic surveys of resources and fishing conditions. The collection of data on the distribution of fish concentrations and on characteristics of water masses allows for studying the structure, commercial significance, quantity, and biomass of commercial concentrations in relation to environmental parameters. The comparison of these data in time provides the possibility to determine the quantitative regularities of the spatial and temporal variability of fields of fish concentrations and characteristics of the water medium, as well as the dynamics of their interrelations. All this must significantly increase the efficiency of forecasting resources in traditional commercial regions.

INFORMATION COLLECTION AND TREATMENT

The ichthyologic, oceanographic, and fishing information are collected and treated in the course of fisheries-acoustic surveys. The collection and treatment of ichthyologic and oceanographic data are accomplished exactly as they are when carrying out an acoustic survey. The procedure of this work was described in the previous chapter. The fisheries-acoustic method of determining the density and commercial significance of concentrations constitutes an exception.

The catch, the vertical opening, the technical productivity, and the coefficient of catching ability of trawls of commercial vessels serve as initial data for calculating the density and commercial significance of concentrations. Besides, for estimating the density, the coefficient of the vertical embrace of concentrations is required. The peculiarities of determining all the above-cited parameters are considered in detail in previous sections of the present chapter.

The commercial significance of a concentration is widely used in estimating fishing conditions in regions of active fisheries. The commercial significance is determined by catches taking into account the type and characteristics of trawls used by commercial vessels. If a trawl of the type, which is the most widely applied in a given commercial region, obtains a certain catch, a forecasted catch is taken equal to the actual one per hour of trawling. A catch, obtained by a trawl of another type, is used for estimating the commercial significance after introducing the correction, accounting for the differences in the technical productivity and the coefficient of catching ability of trawls. Such calculations are accomplished from formula (8.6). Sometimes, in carrying out surveys of fishing conditions, for specifying the location of the densest part of a concentration (Figure 8.1), the commercial significance is calculated from integrator readings. Then, either formula (8.4) or (8.5) is used.

Determining the concentration density from commercial data is a pivotal question of fisheries-acoustic surveys. It is necessary to know the concentration density both in surveys of fishing conditions and in surveys of resources. Formula (8.1) is used in calculating the area density by catches. The area concentration density on sections of a region under study, where there is no fishing, is determined by integrator readings. For this purpose, the standard method and relation (6.20) are used.

The treatment of values of the concentration density and commercial significance, received as a result of surveys of fishing conditions and resources, is made by a single method. Values of the area density and commercial significance, calculated with the use of commercial and acoustic data, are plotted on plane tables. The entire range of values of the area density and commercial significance, plotted on a plane table, is divided by several gradations; isolines of the density and commercial significance are drawn for each gradation. As a result, a picture of the location of commercial and noncommercial sections is received for an entire region studied; the biomass of concentrations is estimated.*

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* As in treating data of a purely acoustic survey, plotting of plane tables is currently done with the help of computers.

In analyzing formulas (8.1)–(8.6) for calculating the concentration density and commercial significance by catches, it is possible to find that the source of main errors in all calculations is the coefficient of catching ability of trawls K_Q. The error in calculating the coefficient of the vertical embrace of concentrations K_{vert} is much less, as the errors of the density ρ_{int} and ρ_s from formula (8.3) by the acoustic method are reciprocally cancelled. As a result, according to preliminary estimations, the error of determining the density and commercial significance of concentrations by catches can reach ±30%.

Thus, the accuracy of a fisheries-acoustic survey is, in most cases, of the same order as it is in carrying out a purely acoustic survey. In the cases when there are only a few vessels in a region under study and, subsequently, the number of measurements of the density is comparatively small, the error of fisheries-acoustic surveys can sharply increase. Therefore, when a productive region is only lightly exploited by the fisheries, a purely acoustic survey has to be carried out (see Chapter 7).

STUDY OF THE VARIABILITY OF FISH CONCENTRATIONS

Variability of distribution and behavior is a characteristic peculiarity of the majority of commercial fish: they continually move; migrate to areas of fattening, spawning, or wintering; leave them; and displace inside these regions. The fish distribution in space and time changes strongly under the impacts of their physiological state and of the oceanographic characteristics of water masses. Knowledge of the regularities of fish distribution and behavior, changing under the impact of the mentioned factors, is important in studying interrelations, in forecasting the state of resources and fishing conditions, as well as in designing surveys.[9]

A long-, middle- and short-term duration of variability of fish distribution are differentiated. A long-term duration (seasonal or annual) of variability is connected to the instability of large-scale climatic phenomena and is characterized, first of all, by the variation of routes of migrations and by the water area of habitation of populations. A middle-term duration (within one commercial season) of variability of fish distribution and behavior in places of their accumulation is explained by the instability of atmospheric and oceanic processes and their impact on the biological fish cycle; this often leads to a deviation from the usual dates and rates of formation, development, and disintegration of concentration during fattening, spawning, or wintering. A short-term duration depends on weather conditions. A concentration or, in contrast, a dispersion, of fish or changes in the depth of their habitation can be caused by variations of the cloudiness or sea roughness within the limits of a synoptic cycle.

Studying the dynamics of variation of the biomass is especially effective during spawning or wintering, when fish concentrate on a small area and it is comparatively easy to observe and to estimate them. The value of a biomass, received as a result of surveys carried out within a period of mass fish arrival, characterizes the state of the stock of a population under study. It is necessary to determine the biomass taking into account the fish age composition for revealing less numerous and the most productive generations.

The dynamics of the seasonal variability can be presented as a graph of changes of the biomass in a region of fisheries during a certain period of time. Such a graph is plotted based on data of regular surveys of fishing conditions. The value of the biomass is determined from catches of commercial vessels and is corrected taking into account acoustic observations. For the sake of obviousness, the graph of variation of the biomass is given in idealized form in Figure 8.4. The dashed lines depict the initial and final sections of the curve, as no fisheries on small concentrations are carried out.

The curve in the figure gives an idea about the beginning of the mass fish arrival to a region, the duration of existence, and the rate of variability of commercial concentrations. The period of existence of concentration Δt is the time interval, during which the value of the biomass decreases no more than 50% from its maximal level. The narrower the curve, the shorter is the period of existence of commercial concentrations, and the more intensive is the fish arrival to a region and exit from it.

The rate of changes of the biomass T_w in a commercial region is estimated by the increase or decrease of the fish quantity in unit of time (in tons per day). It follows from the graph that the average rate of increasing or decreasing the biomass is calculated from the relation

$$T_w = \frac{W_2 - W_1}{t_2 - t_1}$$

or

$$T_w = \frac{W_3 - W_4}{t_4 - t_3} \tag{8.8}$$

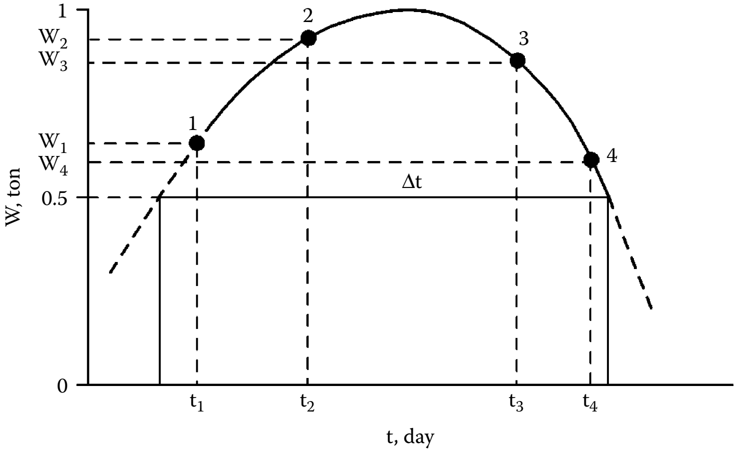

FIGURE 8.4 Diagram of the temporal change of biomass of fish concentrations in a commercial region.

The rate of varying the biomass, to some extent, characterizes the dynamic of the fish motion; a high rate corresponds to intensive fish motion, while, with the slump of migrations, the rate of changing the biomass becomes low.

The knowledge of regularities of variation of the biomass in a traditional region provides the possibility of correctly choosing the time favorable for carrying out a survey of resources, when the majority of a population gathers in this region. A survey for estimating a stock should be started immediately after the end of the growth of a biomass; i.e., near its maximum.

Plane tables of the distribution of the concentration density, plotted by the standard method, are widely used for a visual analysis. Borders of commercial concentrations and their density distribution are determined by the configuration of isolines on a plane table. The treatment of a series of plane tables provides a possibility of revealing and specifying regularities of the development of the processes of variability.

The short duration of fisheries-acoustic surveys reduces to zero the asynchronous character of measurements, ensures an undistorted presentation on plane tables of fields of density of fish concentrations and environmental parameters, and allows, practically with no error, for quantitatively observing their variation in space and time.

Characteristics of the seasonal and annual variability of fish concentration are studied during surveys of fishing conditions in a region within periods of fattening, spawning, or wintering. In a region of operation of the fishing fleet, it is enough to carry out such surveys only once within a synoptic period during a comparatively calm state of the sea; surveys should be conducted not only within the limits of a commercial region, but also on its periphery to reveal the direction of fish migration to a region, and departure from it.

Carrying out regular surveys of fishing conditions in a region of operation of the commercial fleet provides a possibility of following the dynamics in the redistribution of fish concentrations (Figure 8.5). Conducting a series of surveys also allows for studying the dynamics of temporal changes of the concentration density, the area of distribution, the depths of habitation, and other quantitative characteristics of fish concentrations, in connection with environmental conditions (Figure 8.6).

For elucidation of the degree of variability of processes, it is possible to use correlation series of measured parameters, graphically presenting them as isocorrelates, which show changes in space or time of the structure of the distribution of a field studied. Then, the analysis of plane tables of isocorrelates of fish concentration and environmental parameters will allow for representing quantitatively the degree of nonuniformity of a field, zones of partition and transformation, and the spatial and temporal variability.

Spatial and temporal structure functions play an important role as a measure of nonuniformity of the distribution of parameters of concentrations and the medium. Quantitatively, structure functions represent the averaged square of the difference of measured values of a parameter studied on a certain spatial or temporal interval.

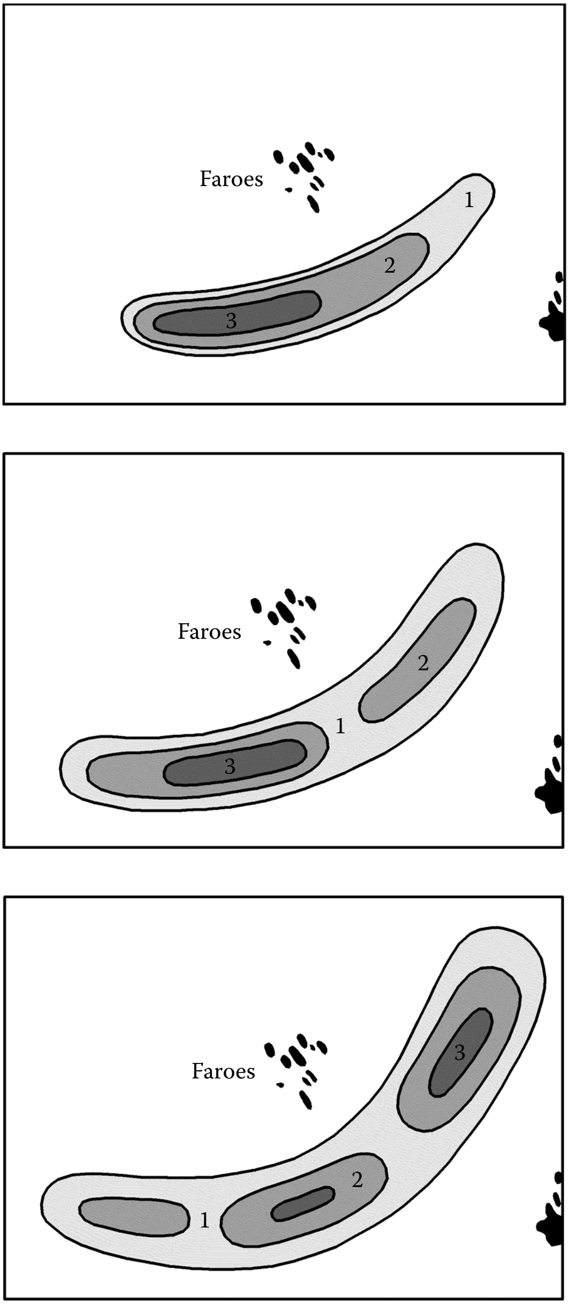

FIGURE 8.5 The plane table of the distribution of area density of blue whiting concentrations, Norway Sea, Faroe zone, May. Top: first decade of the month; Middle: second decade; Bottom: third decade. 1, $10 < \rho_s < 40$ tons/mile^2; 2, $40 < \rho_s < 80$ tons/mile^2; 3, $80 < \rho_s < 160$ tons/mile^2.

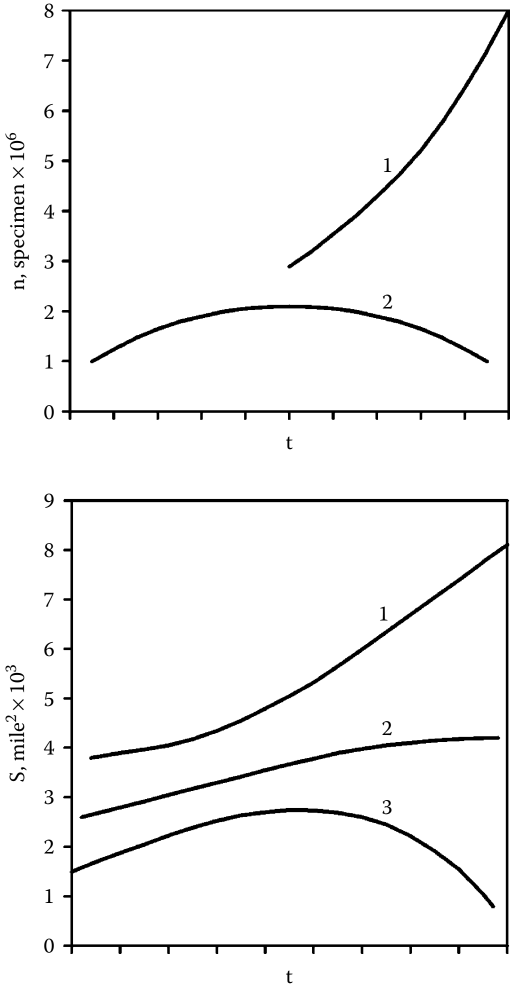

FIGURE 8.6 Diagram of the temporal change of the following parameters: Top: quantity (1, younger ages, 2, elder ones); Bottom: the area of concentrations (1, younger ages; 2, middle ages; 3, elder ones).

The spatial structure function regarding the distribution of commercial concentrations is determined from the following formula[10]:

$$B = \overline{\left[\rho\left(x + l_{\text{int}}\right) - \rho\left(x\right)\right]^2} \tag{8.9}$$

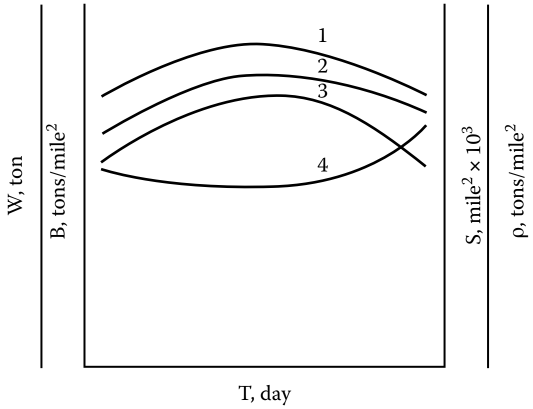

FIGURE 8.7 Dependence of the following parameters on the duration of observations: 1, biomass; 2, area; 3, average concentration density; 4, structural function.

as a result of fish migrations within a commercial region or outside its limits leads to a noticeable decrease in the values of ρ_s and S. Simultaneously, the structure of concentrations change: their horizontal and vertical dimensions decrease, the nonuniformity of the fish distribution increases; i.e., the values of the spatial structure function B grow.

Under certain conditions, an abrupt decrease of values ρ_s, W, S, and increase of B occurs, which forecasts the disintegration of concentrations and mass fish migrations to another region. Therefore, it is important to know the limiting values of ρ_s, W, S, and B, with which the state of fish concentrations becomes unstable. This will allow a timely foreseeing of the disintegration of concentrations and facilitate moving the commercial fleet to a more productive region.

It is no less important to know the annual dependence of values ρ_s and S on the state of stocks and environmental conditions. The accumulation of information on the dynamics of spatial and temporal changes of concentrations in traditional commercial regions for many years and the comparison of results of the last surveys with retrospective analogs will allow for receiving an idea on the variation of the quantity of a commercial population. Such verification of the state of a commercial population is sometimes necessary with the intensive exploitation of biological resources, especially regarding fish with great fluctuations of recruitment, when the size of a population depends on weather conditions to a significant degree and can change sharply from year to year.

Annual measurements of values ρ_s, W, and S during periods of fattening, spawning, and wintering will allow for construction of graphs of quantitative changes of these values by seasons and years regarding various species at different basins, as well as for determining their allowable values; the decrease of stocks below those values can cause an interdiction of fisheries.

It should be noted that results of studying the dynamics of commercial concentrations would be still more useful if they were successfully connected with envi-

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It should be noted that results of studying the dynamics of commercial concentrations would be still more useful if they were successfully connected with environmental characteristics and the physiological fish state, the variability of which also requires permanent monitoring.

Study of Ecosystem Relationships of Natural Processes

To use the results of variability of fish concentrations for forecasting, it is important to investigate the impact of environmental conditions and the physiologic state on redistribution of commercial concentrations. Materials of periodic acoustic surveys, as well as concurrent oceanographic and trawling stations, help in studies of general regularities of the impact of physical conditions, food sources, physiologic state, length, and age composition on the character, structure, horizontal and vertical distribution, and density and quantity of concentrations.

Because of the great variability of environmental parameters and the distribution of biologic items, a detailed study of interrelations must be accomplished dynamically. In this sense, carrying out a series of rapid multidisciplinary surveys is rather important. When such surveys will be further developed, rapid multidisciplinary measurements will allow for studying the variability in detail, not only of fish concentrations, but also of temperature, plankton, and other oceanographic parameters, as well as providing a deeper understanding of the influence of environmental conditions on fish distribution and behavior, taking into account the interaction of various species with one another (see Section 8.4).

To conserve the stability of ecological systems, control is required of stocks of both the main commercial population and of the other species of ecosystems. For this purpose, it is important to know the dependences of the distribution and quantity of biological items on the rate of growth, predation, and other factors under various environmental conditions. Knowledge of such interrelations is necessary for long-term as well as seasonal forecasting.

In studying interrelations within the framework of an ecosystem, ecological surveys will provide a possibility of determining the quantity of predators and prey in a region under study, their daily ration, and the degree of consumption of one species by the others, taking into account the physical conditions and other factors of the medium. Knowing the quantity and the daily ration of the main fish species, it is possible to quantitatively estimate feeding interrelations as well as conditions under which predation between various species and cannibalism will be observed.

As the study of quantitative interrelations deepens, it will become possible to more accurately forecast resources of various species and to correct their commercial withdrawal. Such a correction of resources of fish, which are predators or competitors in relation to one another, will allow for approaching an optimal ratio of species.

For competent forecasting, it is important to examine the principles of formation and disintegration of commercial concentrations. The analysis of results of regular ecological surveys will allow for observing the dynamics of the spatial and temporal variation in the distribution of commercial concentrations and of the main environmental parameters and their interrelations, as well as revealing dominating factors influencing the formation of concentrations.

The accumulation of information on spatial and temporal changes of fields of fish concentrations and characteristics of water masses and the comparison of these data will allow for dynamically estimating the impact of priority factors of the external medium on the fish distribution. As a result, it will be possible to determine more accurately the optimal conditions for the appearance of concentrations of various biological items within each commercial season, as well as the role of different factors in the formation of concentrations.

Regular ecological surveys in commercial regions will provide a possibility of receiving quantitative dependences of the impact of various environmental factors on the distribution and behavior of biological items. As investigations of quantitative interrelations widen and deepen, the transition from a qualitative character of forecasting, often based on the expert's analysis, to a numerical simulation of ecosystem processes will become possible; this, in turn, will allow for more accurate estimating and forecasting of stocks and will improve the regulation of fisheries.

USE OF SURVEY RESULTS FOR FORECASTING

Knowledge of regularities of the distribution and behavior of fish under the impact of various factors allows for better forecasting of the state of resources and fishing conditions. It is believed that the development of ecological surveys will promote an increase in the accuracy of the mentioned forecasts.

It is known that forecasts may be made in advance with various durations of the beforehand period: long-term, seasonal, and short-term. Long-term duration forecasts are made for a term of 1.0–1.5 years. Seasonal forecasting is often necessary with a strained state of stocks. Forecasts of long-term duration and of a seasonal one are built on the basis of biological methods, which give the possibility to receive information on the state of commercial resources and tendencies of their variation, as well as to forecast a general allowable catch and quotas for periods to come.

Results of surveys of commercial resources are often used in long-term and seasonal forecasts of the state of stocks as initial data. Such surveys allow for determining, in a commercial region, the quantity and biomass of the main fish species by ages. An important precondition of a survey of resources is the coverage of the main area of the distribution of a commercial part of a population. Survey results usually serve as verification of biological estimates of the state of stocks.

Data on the concentration distribution, quantity, and biomass, received with the help of a survey of commercial resources and linked with oceanographic characteristics of the medium and the physiologic conditions of the fish, are compared with the forecasted stock for a given period. If there are significant deviations of an estimate of commercial resources from forecasted values, necessary steps are taken;

for instance, corrections to a forecasted value of the commercial withdrawal are introduced.

Seasonal forecasting is also required for estimation of fishing conditions in a productive region. In contrast to a forecast of the state of stocks, aimed mainly at estimating the quantity and biomass, a seasonal forecast of fishing conditions (quarterly or monthly) is based on the prediction of the distribution and behavior of items, the direction and speed of migrations, the periods of fish mass arrival to a region, and the possible catches. Forecasting the periods of a mass fish arrival to a region is important not only for estimation of fishing conditions, but also for the correct design of the place and time of carrying out a survey of resources.

Already established, based on averaged data, general dependences of the impact of the medium on the distribution and behavior of fish, the productivity of generations, and the quantity and biomass of various species of commercial items are used in making seasonal forecasts of resources and fishing conditions. Such forecasts are often made by the method of analogies based on comparison of survey results with existing data, retrospective and averaged for many years. This method allows for reception of a tentative forecast.

The use of the principle of sliding forecasting, accounting for the inertia of processes, gives slightly better results. For instance, in forecasting fishing conditions for a month, first a tentative forecast for this time period is made. After two weeks, the forecast for the following two weeks is corrected, taking into account the results of surveys of fishing conditions and outlined tendencies in the distribution of fish concentrations; simultaneously, the following forecast for another month is made. In successively carrying out the mentioned operations and control surveys, a forecast is continuously, successfully improved.

However, the existing methods of seasonal forecasting do not always give reliable enough results because of the great variability of natural processes. In applying fisheries-acoustic surveys, the task of short-term forecasting of the distribution of concentrations and possible catches for the comparatively stable period of a synoptic cycle, the duration of which is 5–10 days, and in the summer, more, can be easily solved. True, an abrupt variation of weather conditions may sometimes change the distribution of concentrations in a commercial region, literally for several hours. Therefore, short-term forecasts of fishing conditions can be made 1–3 days before fishing in unstable weather.

Especially frequent surveys of fishing conditions are required to ensure the reliability of short-term forecasts. The practice of carrying out frequent fisheries-acoustic surveys in previous years showed that the comparison of a series of plane tables allowed revelation of typical tendencies in the redistribution of concentrations. Accurate enough forecasts were made based on tendencies established and meteorological forecasts.

MONITORING SERVICE

It follows from the above that the self-repayment and great operability is an important quality of fisheries-acoustic surveys. They are a decisive factor for the wide development of monitoring of resources and fishing conditions. Regular carrying-out of frequent fisheries-acoustic surveys and concurrent oceanographic and commercial stations in different regions and for various items, the collection, treatment, and analysis of numerous data require the creation of special services for the monitoring of basins.[11]

Created in Japan, Norway, the United States, and other countries, centers of control and regulation of marine biological resources are examples of the organization of such services. Services in Japan are especially efficient. In particular, the transmission of data on fish concentrations, their behavior, and the efficiency of fishing in a standard format is a necessary condition of commercial work of Japanese fishermen. Fishermen are given a bonus for high-quality information. The oceanographic information is received from research vessels, satellites, meteorological centers, and so on. A powerful information service and an efficient system of collection, treatment, and analysis of data at shore centers allow for making accurate enough forecasts of the state of stocks and their exploitation.

Monitoring services on research vessels should be provided with qualified acousticians, oceanographers, ichthyologists, and specialists in electronic and computer technique. The monitoring of resources and fishing conditions should be conducted on scientific vessels provided with modern navigation, acoustic, oceanographic equipment, and computers. It is expedient that these vessels would implement the functions of staff so the management of fisheries could use the latest information about the state of resources and fishing conditions for designing the operation of the fisheries fleet.

Experts of the monitoring service, in addition to control of biological resources and fishing conditions in a region, short-term forecast, and study of ecological interrelations, must ensure the operative maintenance of fisheries vessels by providing them with actual and forecasting plane tables of the distribution of concentrations by their commercial significance, as well as graphs of the distribution of commercial significance by depths. Such graphs and plane tables ensure more efficient fishing, as they allow for better orientation within a situation, choosing the most productive sections of concentrations and the optimal regimes for use of trawls. During intervals between fisheries-acoustic surveys, there is also the possibility of helping fishermen in mastering navigation, acoustic, and oceanographic equipment.

In serving fishermen, it is possible to simultaneously control the efficiency of operation of commercial vessels. The point is that, by regularly carrying out fisheries-acoustic surveys of a region, in the course of analyzing catches of fishing vessels at sections of concentrations with the same commercial significance, it is easy to identify vessels operating with a low productivity.

Low indices of a catch may chronically take place because of a non-qualitative cut-out of a trawl, its bad rigging and adjustment, incorrectly chosen tactics of aimed catching, the speed of trawling, or the opening and the horizon of trawl motion. In conducting special acoustic observations and measurements, it is possible to elucidate reasons for low trawl productivity and to make recommendations for improvement. As a criterion of the efficiency of the work of a trawl, it is expedient to use its coefficient of catching ability, which is determined by the acoustic method before and after the removal of troubles.

Such an activity of experts of the monitoring service will promote the increase of the accuracy of survey results, e.g., raising the productivity of badly operating vessels improves the averaged indices of coefficients of catching ability of trawling complexes and allows for receiving more objective calculated values of the density and commercial significance by catches when constructing plane tables of the distribution of concentrations.

The permanent control of the efficiency of operation of commercial vessels not only verifies the quality of commercial information, but insures inspection of the course of fisheries and enforcement of their regulations. It is no secret that commercial data are not always reliable and information about low indices of fisheries vessels can be attributed not only to an unskilled commercial operation, but also can be a result of the transmission of incorrect information on catches.

In modern conditions, commercial vessels receive quotas of catch for each voyage in accordance to an established number of the fisheries withdrawal. It would appear that the control of fisheries is a common task of basin research institutes and fish protection authorities. However, no close interaction of vessels of these organizations has been observed as of yet. This is explained by the fact that purely acoustic surveys, carried out by the efforts of institutes, do not ensure the control of fishing conditions within commercial regions.

The systematic control of the course of fisheries and the practical collaboration with fish protection authorities will become possible only after the organization of regular fisheries-acoustic surveys. Especially close cooperation will become possible in the case of joint activity of scientists and inspectors on one vessel.

It has been mentioned that, in the course of a fisheries-acoustic investigation, researchers can ensure the remote control of the correctness of the commercial information transmitted by radio from fisheries vessels. In possessing plane tables of the distribution of fish concentrations by their commercial significance, it becomes easy to spot vessels that give incorrect information on catches.

Special electronic equipment provides a great help in organizing the control of fishing conditions. For this purpose, commercial vessels are equipped with various computer and satellite navigation systems. Fisheries vessels at present are equipped with sensors of coordinates. Blocks of such communication and navigation equipment allow for automatically fixing and broadcasting the current coordinates of a commercial vessel and following its track. A vessel operator is supposed to introduce information on the value and assortment of catches into a block of communication. Such systems of navigation and communication allow for correlating catches with the location of fisheries; this is important information for both the fish protection authorities and for scientists dealing with forecasting.

Such control of the operation of commercial vessels will force fishermen to report correct information. In addition, the practice of servicing commercial vessels has shown that, after receiving actual and forecasted plane tables as well as other useful information on fish redistribution, fishermen recognize the importance of reporting undistorted information.

The mentioned factors should promote the accomplishment of one of the major conditions for carrying out fisheries-acoustic surveys: receipt from commercial vessels of correct information about catches. Therefore, there are grounds to believe that, as the authority of the monitoring service increases, the reliability of the information reported by fishermen will grow; this, in turn, will raise the accuracy of estimating biological resources and fishing conditions.

Summing up all the above-mentioned, we would like to emphasize the great perceptiveness of fisheries-acoustic surveys on research vessels. Regularly conducting such surveys within a framework of the monitoring of resources and fishing conditions ensures a self-repayment of a great complex of investigation and practical work. In this case, errors because of the incorrect choice of the time of the initiation of surveys of the state of stocks and the asynchronous character of measurements of data are excluded; the accuracy of the estimate of commercial resources and environmental parameters increases; the possibility of developing detailed dynamic ecosystem investigations arises, well then the forecasting more precisely commercial resources and their withdrawal. Additionally, efficient operation of a fisheries fleet in commercial regions under investigation is ensured.

REFERENCES

1. Yudanov, K.I., Methods of carrying out surveys of fishing conditions. *Fisheries*, 12, 44, 1986 (in Russian).
2. Yudanov, K.I., Fisheries-acoustic surveys of biological resources on research vessels, *Fisheries*, 1, 47, 1999 (in Russian).
3. Yudanov, K.I., Kalikhman, I.L., Kochikov, V.N., Tesler, W.D., and Kotenev, B.N., *Multidisciplinary Surveys of Fishing Conditions*, VNIRO, Moscow, 75, 1988 (in Russian).
4. Treschov, A.I., *The Intensity of Fisheries*, Pischepromizdat, Moscow, 180, 1983 (in Russian).
5. Anon., *Technical Productivity (Power) of Trawls and Purse Seines*, VNIRO, Moscow, 29, 1983 (in Russian).
6. Bondarenko, V.M., Isaev, N.A., and Yudanov, K.I., Estimation of fishing conditions in the area of blue whiting fisheries, *Fisheries*, 10, 42, 1988 (in Russian).
7. Levashov, D.E., *Facilities and Technique for Marine Surveys: Instrumental Methods and Components for Estimating the Fishing-Significant Characteristics of Water Medium*, VNIRO, Moscow, 400, 2003 (in Russian).
8. Yudanov, K.I., Control of the state of biological resources with the help of fisheries-acoustic surveys, *Fisheries*, 3, 34, 1994 (in Russian).
9. Yudanov, K.I., Study of the variability of the distribution of fish concentrations with the help of accounting surveys, *Fisheries*, 6, 30, 1996 (in Russian).
10. Stull, R.B., *An Introduction to Boundary Layer Meteorology*, Kluwer Academic Publishers, Dordrecht/Boston/London, 666, 1988, 1989, 1991, 1993.
11. Yudanov, K.I., Acoustic monitoring of biological resources and fishing conditions, *Fisheries*, 6, 62, 1991 (in Russian).

9 Passing Observations and Surveys on Commercial Vessels

From economic reasons, it is possible to accomplish the control of the state of biological resources within one's own national waters on fishing vessels. In such cases, research institutes send their scientists to commercial vessels, which carry out passing observations and surveys in traditional commercial regions.

Usually, passing observations and surveys on commercial vessels in regions of the fisheries fleet operation are needed for correcting annual and seasonal forecasts of the allowable withdrawal under a strained state of a stock, as well as for preparing quotas and licenses. In such cases, a commercial vessel is temporarily equipped with the additional acoustic and other equipment.

As acoustic equipment for passing observations and surveys, simple electronic attachments to echo sounders are used on comparatively small commercial vessels.[1] The electronic attachment is an autonomous receiver of a vessel's echo sounder, designed for the reception and treatment of echo signals from fish concentrations in a form convenient for measuring their density and commercial significance.* The electronic attachment is connected to the transducer of a vessel's echo sounder. The attachment has a large dynamic range of the gain, ensuring the registration of commercial items until limiting depths of their habitation, precise TVG laws for individual and multiple targets, and the integration and processor treatment of echo signals from fish concentrations.

A computer, navigation satellite receiver, and other equipment are parts of the electronic attachment. A program of collection of information used directly in the course of passing observations and surveys and a program for the complete treatment of data received are foreseen in the attachment.

The electronic attachment of an echo sounder is simple; this allows biologists and oceanographers, without special training, to carry out passing observations and acoustic surveys. In using the attachment, a short course of instruction provides researchers with the possibility of estimating the density, the commercial significance, and the biomass of detected concentrations.

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* At present, large commercial vessels are equipped with echo sounders with great functional possibilities (Simrad ES60 series). It is possible to use such complexes for long-term passing observations, but inexpedient for surveys, as it is too expensive to divert large vessels from fisheries operations.

9.1 THE PRINCIPLES OF ESTIMATION OF FISH CONCENTRATIONS

It was mentioned in Chapter 7 that, on scientific vessels, measurements connected to the calibration of the equipment with spheres, determining the target strength and the length of composition of fish concentrations, are ensured by a special, complicated technique. It is impossible to accomplish such measurements accurately enough on a commercial vessel, equipped only with an echo sounder with the electronic attachment. Therefore, we suggest a simplified version of calibration of acoustic equipment; it is possible to estimate the density and commercial significance of concentrations by catches.

Estimation of Possible Catch and Commercial Significance of Concentrations

As mentioned in the previous chapters, the intensity (energy) of echo signals from item concentrations is proportional to the number insonified by an echo sounder, and then, to catches Y; i.e.,

$$Y = CM_{\text{trawl}} \tag{9.1}$$

where C is the constant of the acoustic equipment and M_{trawl} is the summary echo intensity of concentrations within a layer caught.

The summary echo intensity within a layer caught is measured with the help of an integrator of the electronic attachment. The unit of sampling distance is taken equal to the extension of trawling. Measured values of M_{trawl} are fixed on the display of the equipment. It is possible to use the results of calculations by formula (9.1) in commercial work. For this purpose, a relation of the intensity of echo signals of fish concentrations and the catches is drawn. As an example, such a graphical relation is presented in Figure 9.1**.** The graph allows fishermen to estimate the possible catch on detected fish concentrations, and, during the course of trawling, to forecast the catch and to determine the optimal time of lifting the trawl.

It should be taken into consideration that the speed of the vessel, when carrying out passing observations, surveys, or a local search v_{vess}, is usually higher than in trawling v_{trawl}. Therefore, when working at the chosen range of an echo sounder, the number of echo signals, and then the summary echo intensity M_{trawl} from fish concentrations, at the same interval of integration, decreases as compared with trawling at about $v_{\text{vess}}/v_{\text{trawl}}$ times. One should multiply the echo intensity by $v_{\text{vess}}/v_{\text{trawl}}$ when observing or surveying to compensate for this phenomenon. In this case, to determine the supposed catch or the commercial significance of concentrations Q at a chosen section of the path of a vessel, formula (9.1) will have the following look:

$$Y = Q = CM_{\text{trawl}}(v_{\text{vess}}/v_{\text{trawl}}) \tag{9.2}$$

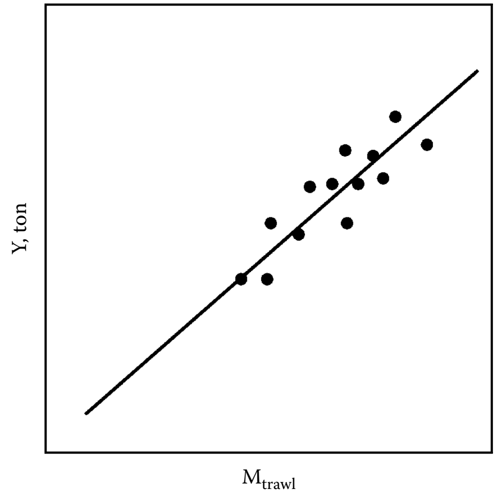

FIGURE 9.1 The relation between the echo integrator readings and the catches.

ESTIMATION OF DENSITY OF FISH CONCENTRATIONS

In carrying out a survey or search work, when estimating the biomass of concentrations is required, catches of a commercial vessel are recalculated to the value of the density of concentrations from formula (8.1). If the duration of integration on the path of a vessel differs from one hour, the value of the technical productivity of a trawl in formula (8.1) should be multiplied by the time of integration over the fractions of an hour t.

Substituting relation (9.2) into (8.1), the following formula for calculating the area density of concentrations, detected in carrying out a survey, search, or passage, is received:

$$\rho_s = \frac{3.4 \times 10^6 r_{int} C M_{trawl} \left(v_{vess} / v_{trawl} \right)}{K_Q K_{vert} W_{trawl} t} \tag{9.3}$$

In calculating the coefficient K_{vert} (formula 8.3), echo intensities M_{trawl} and M_s are used instead of densities. If the circumstance that echo intensities are proportional to the volume concentration density is taken into account, it is possible to determine the value K_{vert} as

$$K_{vert} = (M_{trawl}/M_s) x (h_{int}/h) \tag{9.4}$$

where M_{trawl} and M_s are echo intensities from fish concentrations within a layer of their fishing h_{int} and by the entire thickness of concentrations h, respectively; and h is the vertical extension of concentrations.

Control measurement of M_{trawl} and M_s are conducted during acoustic observations in searching and trawling. Averaged values of the coefficient K_{vert} are determined from the results of such measurement.

It is important to know the volume density of commercial concentrations (in sp/m^3) for a quantitative analysis of their distribution. The recalculation of catches of a commercial vessel into the averaged values of the volume concentration density in searching, trawling, or passing can be made from the following formula:

$$\rho_v = \frac{10^6 C M_{trawl} \left(v_{vess} / v_{trawl} \right)}{w K_Q W_{trawl} t} \qquad (9.5)$$

It is impossible to determine the value of the coefficient of catching ability of a trawl on a commercial vessel, as an estimate of the value ρ_{int} acquired by the acoustic method is required for this (formula 8.2). Therefore, the values K_Q received on a scientific vessel are used in calculations of ρ_s and ρ_v from formulas (9.3) and (9.5).

It should be taken into account that the main error in determining ρ_s and ρ_v are given by the coefficient of catching ability of a trawl; it may reach 30–40%. Errors of measuring the other parameters, given in formulas (9.3) and (9.5), only slightly influence the reliability of the concentration density. Therefore, the error of determining the concentration density by the suggested method is of the same order as that estimated by the standard method.[2]

EQUIPMENT CALIBRATION

It is necessary to know the constant of the equipment to determine the commercial significance and the volume and area densities of concentrations from formulas (9.1), (9.3), and (9.5). For this purpose, the calibration of the equipment by catches is conducted during the fisheries operation of a commercial vessel.

The calibration of the equipment is reduced to the determination of the echo intensity from concentrations accumulated by an integrator within a layer of their fishing in carrying out a series of trawling. The values of catches are compared with the integrator readings on tracks of trawling. As a result of such measurements, the constant is received:

$$C = Y/M_{trawl} \qquad (9.6)$$

The calibration of the equipment does not require any preliminary operations; it is carried out repeatedly during the course of fishing, without diverting a vessel from commercial work. Therefore, it is possible to determine, without difficulty, the average value of the constant of the equipment by a great number of trawls when it is required. The regimes chosen for the work of the equipment and of the trawl should remain invariable, both during the measurements of the equipment constant and during the course of surveys, local searches, and passing observations. Operating in a commercial region, the regimes of the equipment and the trawl are changed very rarely; in those cases, it is necessary to carry out a recalibration.

It follows from relation (9.6) that the equipment constant is determined by values of catches and echo intensity from fish concentrations within the water column.* In turn, catches and readings M_{trawl} depend on the character of the distribution and behavior of fish. Comparatively small deviations from correct values of C can be tolerated in calibrating the equipment by concentrations, when the fish are only slightly active and the coefficient of catching ability of a trawl changes insignificantly.

Fish in schools are sensitive to the approach of a trawl; as a result, the catching ability of a trawl can vary over great ranges. In this case, fish readings of an echo sounder often do not coincide with catches, as schools move away from a vessel and trawl. Only when all schools or a significant part is completely captured by a trawl do readings of M_{trawl} correspond to catches. As a result, the dispersion of values of the equipment constant under the schooled distribution can be great.

A significant variation of values of the equipment constant can occur with vertical migrations, when the target strength and echo intensity from fish concentrations vary greatly because of the inclination of fish bodies and their swim bladders. In this connection, it is not recommended to carry out a calibration during vertical migrations.

9.2 SURVEYS OF COMMERCIAL RESOURCES

A survey of resources with the use of the electronic attachment is conducted on either one or several fisheries vessels, which are diverted for a short time from the commercial operation. If a survey in a designated region is supposed to be carried out without any preliminary investigation, it is necessary to first become familiar with fishing conditions by radio transmissions. Several transects are made; the acoustic equipment is calibrated by catches.

To ensure that survey results characterize the state of commercial resources, efforts are exerted to carry out a survey during the maximal fish migration into a designated region. It is best to determine this time by preliminary passing observations.

The tactics on a commercial vessel are the same as on a scientific one (see Section 7.1). A series of transects is designed and conducted in a designated region according to the standard acoustic method; integrator readings are taken for the determined unit of sampling distance along the path of a vessel; average values of the area density of concentrations are determined; plane tables of the density distribution over the area are drawn; and values of the quantity and biomass of commercial concentrations are calculated.

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* In contrast to concentrations within the water column, concentrations near the surface or at the bottom are only partially registered by an echo sounder; therefore, the accuracy of calibrating and estimating such concentrations is significantly lower than that achieved regarding concentrations situated within the water column (similar to the use of the standard method).

It should be noted that, in carrying out a survey on a fisheries vessel, in contrast to the research variant, trawling is more frequently conducted to specify the correctness of the calibration of the equipment.[3] Specifications of the equipment constant are required for a changeable character of fish registration on the echogram. Especially frequent corrections of the calibration are necessary when fish keep within the bottom layer.

9.3 PASSING OBSERVATIONS

To control the state of resources in a fisheries region, passing observations are carried out in addition to surveys. Such observations should not divert the fishing operations of a commercial vessel. Observations of the state of resources during the fattening are conducted within periods when the bulk of the fish gather in a traditional commercial region. Observations are also undertaken during the mass fish spawning. In the indicated cases, under mass migration, fish gather into rather dense commercial concentrations; the fisheries fleet operates on these concentrations.

It has been mentioned in the previous chapters that the time of mass fish migration to a region depends on their biological state and weather conditions. Taking this fact into account, in carrying out passing observations it is necessary to accumulate the fisheries, ichthyologic, physical, and other information within traditional regions, during different seasons, in order to specify the influence of various factors on the intensity, area, and duration of fish motion.

Observers study the information on catches and regimes of operation of the fisheries fleet by radio transmissions. Using the information received by a radio, observers fix on a plane table the location of fisheries vessels and their catches, reduced to one hour of trawling. When a great density of fisheries vessels exists, vessels operate along parallel courses. In this case, plane tables of the location of parallel tracks of trawling are drawn. Plane tables provide an idea about the distribution, dimensions, and commercial significance of concentrations caught by the fleet.

Observers receive diverse ichthyologic information from trawling catches. A species, length, age, sexual, and weight composition of fish concentrations, the stage of maturity, the fattiness, the stomach content, the food composition, and other indices are determined from ichthyologic samples.

Observers collect the echo sounder information on the fish distribution during trawling, local searches, and passages. As a result of these observations, the following information is determined: how fish keep in a region (dispersedly, in schools or concentrations); what the extensions of fish concentrations are by area and depth; at what depths they are distributed; what the vertical and horizontal migrations are; how fish are redistributed in the course of migrations; and so on. Using an electronic attachment to the echo sounder, the volume and area densities, as well as the commercial significance of fish concentrations, are found. In determining the area concentration density during passing observations in traditional fisheries regions, it is possible to calculate the biomass of concentrations.

Oceanographic observations are carried out only during the non-fishing times; for instance, at night if there is no fishing or while repairing a trawl. Then, oceanographic stations are conducted with the measurement of temperature, oxygen, plankton, and other environmental characteristics at various depths. Observers also receive oceanographic information in a region from the meteorological service and satellite remote sensing of the surface layer of the ocean.

Results of a multidisciplinary passing observation are used in forecasting the state of stocks. For this purpose, measured parameters of fish concentrations are linked with biologic indices of fish, productive and nonproductive generations, climatic conditions, and so on. Analysis of the enumerated factors allows one to make a judgment about possible variations in stocks for a future time period.

Unfortunately, it is only possible to successfully carry out passing observations on fisheries vessels irregularly, episodically. The drastic solution to the problem of the regular control of commercial resources in the main fishing regions will become possible, in our opinion, only as a result of organizing and inculcating economically justified, long-term passing observations on fisheries vessels.

9.4 LONG-TERM PASSING OBSERVATIONS

It was mentioned in Section 8.2 that long-term observations of fishing conditions in a region of operation of the fisheries fleet allow for revealing tendencies in the dynamics of the distribution of fish concentrations. Based on such observations, plane tables of the redistribution of fish concentrations have been successfully drawn.[4] Regular transmissions to fishermen of the forecasting plane tables with corresponding recommendations have significantly increased the catches of the commercial fleet. As a result, the exploitation of the scientific vessel, used for the observation of fishing conditions, was more than compensated.

It is clear that the work of a fishing vessel with observers in the regime of estimation of fishing conditions will also be profitable. It is the most expedient method of carrying out such works in traditional regions on a flagship or headquarters vessel; in this case, it is easier for observers, with the help of a manager of fisheries, to receive by the radio more reliable and detailed information from fishermen.

Working in the mentioned regime, observers elucidate peculiarities of fish distribution and behavior with the help of acoustic measurements. They measure the volume density of fish concentrations with the electronic attachment to an echo sounder. The retrospective values of the coefficient of catching ability of a trawl, received on a scientific vessel, are used. Graphs of vertical sections of the volume concentration density, received through multilayer integration at various depths, give some idea about their structure (see Figure 7.1).

In solving operative tasks, it is useful to estimate fish concentrations from the point of view of their commercial significance. It might also be helpful to measure the commercial significance of concentrations by several channels of integration at different depths. A graph of the distribution of commercial significance by depth is plotted in exactly the same way as is done in conducting a vertical section of the volume density. Such a graph allows for recommending optimal horizons of fishing and the opening of trawls (see Figure 8.2).

The regular treatment of data on the location of fishing vessels and their catches provides the possibility of constructing a series of plane tables of the distribution of fish concentrations at places of operation of the commercial fleet (Figure 9.2). Analyzing a series of plane tables and graphs in time, it is possible to follow the dynamics of the variability of fish concentrations. It is important to know this variability in preparing forecasts of fishing conditions and forecasting plane tables of the distribution of fish; the direction, speed, and intensity of their motion; possible catches; and so on. Data on the distribution of fish concentrations, on tendencies in their displacements, on forecasting productive areas, as well as other useful information, are supplied to managers of fisheries.

Taking into account the self-repayment of the long-term exploitation of a fishing vessel with observers, carrying out investigations of the variability of the fish distribution, biomass, and quantity in relation to environmental parameters becomes more realistic, all the more that it is possible to conduct such works in parallel with observations of fishing conditions.

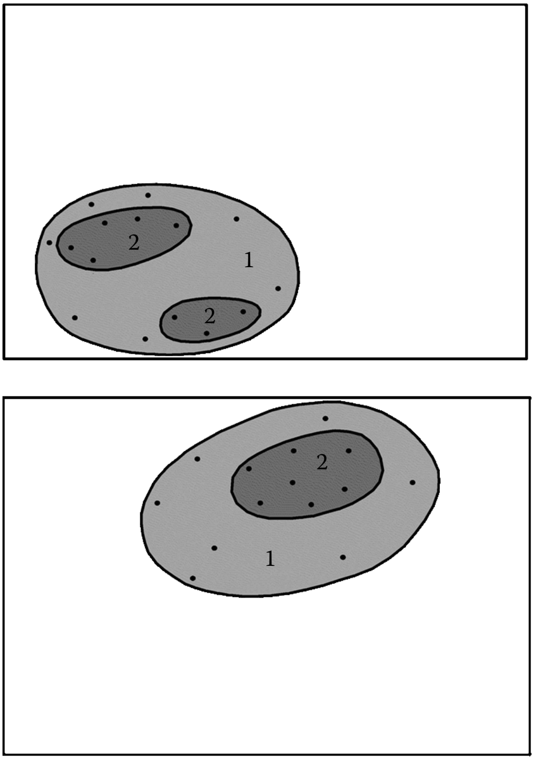

FIGURE 9.2 The plane table of the location of the fishing vessels during various times of fisheries: Top: the end of the first month; Bottom: the middle of the second month. Both plane tables show the same sections of water area. The points show the location of fishing operations. The numbers indicate the following values of commercial significance of concentrations: 1, more than 3 tons/hour; 2, more than 5 tons/hour.

9.5 ANALYSIS OF RESULTS OF OBSERVATIONS

An important quality of long-term passing observations in a region of the fishing fleet operation is the possibility of studying the mechanism of redistribution of fish concentrations. The extension, density and structure of the concentration, and the depth of item habitation are estimated in the course of such observations. Carrying out of such observations during a commercial season opens up the possibility of following the dynamics of changes of these parameters in time, linking them with environmental conditions.

Such investigations should be carried out in especially great detail within a period of intensive fish migration to a region, when the fisheries are actively under way. It is possible to make a judgment about the approach of the period of mass fish migration by sensing the increase in the density of fish concentrations and their horizontal and vertical dimensions; in this case, catches of commercial vessels grow accordingly. In the course of such observations, average catches of fishing vessels are determined from radio transmissions: areas of concentrations from echograms, and their volume density with the help of the electronic attachment.

The dynamics of the variability of fish concentrations in time can be represented by a graph of changes of the general area of concentrations and the average value of their density, as well as catches. It should be taken into account that catches and the volume concentration density strongly depend on the character of the fish distribution and are comparatively weakly connected with the area of concentrations. Thus, under an identical general biomass of concentrations, catches may be light if fish keep dispersedly over a large area; and, in contrast, heavy catches can take place when fish form dense concentrations over a small area. Therefore, temporal maximums of catches and general areas of concentrations do not often coincide on the graph.

A graph of the temporal variability of catches, the density, and the area of fish concentrations is shown schematically in Figure 9.3. The curves are given in a smoothed form in the graph. It is known that synoptic cycles, the biological state of fish, and other factors affect the value of the density and area of concentrations, well then the values of catches. Long-term observations will allow for establishing the regularities of such variations.

The curves in this figure give an idea about the beginning of the mass fish migration to a region, the duration of the existence, and the rate of variability of fish concentrations. In addition, in using the graph, it is possible to determine the time of the maximal fish migration to a region, as well as the degree of the noncorrespondence of the maximal values of concentrations densities, area, and catches, and the reasons for such a noncorrespondence. It is important for the objective estimation of the state of commercial resources under investigation, as well as for the comparison of such estimates by seasons and years, taking into account environmental conditions.

In the course of carrying out long-term observations, it is necessary to continuously determine the averaged values of concentration density, area, and catches, following their variations in time. It is known that the abrupt decrease of the mentioned values foretokens the disintegration of concentrations and mass fish

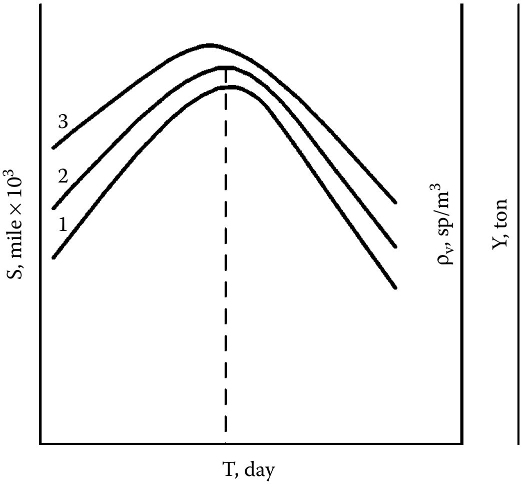

FIGURE 9.3 The dependence of the following parameters of fish concentrations on the duration of observations: 1, catches; 2, volume density; 3, area.

migration to another region. It is possible that the study of the variability of concentration density and area, as well as catches in a traditional region during various commercial seasons, will permit estimating more precisely their allowable values, the decrease of commercial resources below which can lead to overfishing.

Knowledge of dependences of fish distribution on various environmental factors is necessary for forecasting and regulation of commercial resources. The point is that the accuracy of the biostatistics, virtual population, and other methods of forecasting stocks of fish, based on the reconstruction of the quantity of generations of commercial resources by age composition of catches, depends on the degree of study of biological regularities of the variability of fish concentrations in response to environmental conditions.

Long-term ichthyologic, physical, and other passing observations, carried out on fishing vessels according to the standard method, provide a possibility to elucidate and to specify the influence of environmental conditions and fisheries on the character of the distribution of fish concentrations. In this sense, estimates of the density and biomass of concentrations with the help of the electronic attachment play a significant role. As such investigations in traditional commercial regions develop, the accuracy of forecasting resources will grow, and it will become possible to make timely forecasts of either the decrease or increase of stocks and to more reliably design the fisheries withdrawal.

It should be noted that, with the wide use of the electronic attachment on commercial vessels, it may be possible to regularly automatically translate measured values of the density of concentrations, on which the fishing fleet operates, together with current coordinates of a fishing vessel, the depth, the value, and assortment of catches, from commercial vessels to a shore computer center (see Section 8.5). A complete treatment and analysis of these data will allow for following variations of commercial concentrations, comparing variations by seasons and years. This is necessary to correctly regulate the fisheries in a region under observation.

In anticipation of this, we consider that, as the electronic, information, and other techniques improve, they will be more and more widely used by the commercial fleet. It can be stated with assurance that the time will come when the equipment for determining the density of commercial concentrations will be a part of every fishing vessel. This will provide the tools required to solve the problem of estimating and controlling the biological resources of the World Ocean.

Receiving data on the density of commercial concentrations at places of operation of the fishing fleet and translating these data to shore computer centers will allow for receiving a simultaneous picture of the distribution of the biomass of concentrations in commercial regions without carrying out expensive acoustic surveys; it will become possible to continuously monitor biological resources of commercial regions on a global scale. In the course of such a control of the state of stocks, it will be possible to follow the level of the biomass in traditional commercial regions. If the level of the biomass in a controlled region does not correspond to a standard, a scientific vessel will be directed to such a region for carrying out multidisciplinary studies, elucidating the reasons, and subsequently taking the required steps.

REFERENCES

1. Bondarenko, V.M. and Yudanov, K.I., Use of an echo integrator on a fishing vessel, *Fisheries*, 9, 66, 1990 (in Russian).
2. Kalikhman, I.L., Estimating the accuracy of the determination of fish concentration density by acoustic method, in Proceedings of the Institute of Biology of Inland Waters, Academy of Science of the USSR, Estimating Errors of Hydroacoustical and Ichthyological Investigations, *Rybinsk*, 49(52), 103, 1982 (in Russian).
3. Yudanov, K.I., Tactics of surveys of biological resources on fishing vessels, *Fisheries*, 1, 34, 1998 (in Russian).
4. Bondarenko, V.M., Isaev, N.A., and Yudanov, K.I., Estimation of fishing conditions in the area of blue whiting fisheries, *Fisheries*, 10, 42, 1988 (in Russian).